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AN INVESTIGATION OF THREE EXTREMITY ARMOR SYSTEMS: DETERMINATION OF PHYSIOLOGICAL, BIOMECHANICAL, AND PHYSICAL PERFORMANCE EFFECTS AND QUANTIFICATION OF BODY AREA COVERAGE

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14. ABSTRACT

This report documents an evaluation of three personal protective systems designed to be worn with armor vests for the ballistic protection of the arms and legs. The systems were similar in weight (~6 kg), but differed in the extent of the body surface area they covered. Eleven Army enlisted men participated in the assessment of the relative effects of the extremity armor and of an armor vest worn alone on physiological, biomechanical, and maximal performance measures. It was found that times to complete 30-m rushes and an obstacle course run were fastest with the armor vest alone and slowest when the extremity armor with the greatest body area coverage was used. Rate of oxygen uptake, a measure of energy consumption, was recorded during treadmill walking and running and scaled to body mass for analysis. These data yielded lower energy consumption with the armor vest alone than with the extremity armor. Gait kinematics and kinetics were also recorded during the walking and running, and spatio-temporal gait variables and ground reaction force variables were computed. Analyses of these data revealed differences between the armor vest worn alone and with the extremity armor systems, but there were few differences among the extremity armor systems. Of the three systems, 10 of the 11 study participants preferred to wear the system with the least body area coverage.

15. SUBJECT TERMS

GAIT	VARIABLES	LOCOMOTION	ARMY PERSONNEL	BALLISTIC PROTECTION
LEGS	BODY ARMOR	METABOLISM	RANGE OF MOTION	ANALYSIS OF VARIANCE
VESTS	COMPARISON	BIOMECHANICS	PERFORMANCE(HUMAN)	PROTECTIVE EQUIPMENT
WALKING	ENERGY COST	OXYGEN UPTAKE	TEST AND EVALUATION	PHYSIOLOGICAL EFFECTS
RUNNING	EXTREMITIES	METABOLIC COST	PERSONAL PROTECTION SYSTEMS	
MOBILITY	KINEMATICS	ARMS(ANATOMY)	PPE(PERSONAL PROTECTIVE EQUIPMENT)	

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PREFACE

The study reported here was carried out during the period from February 2007 to May 2008 by personnel of the Biomechanics Team, Warfighter Science, Technology and Applied Research Directorate, Natick Soldier Research, Development and Engineering Center. The purpose was to provide an evaluation of the physiological, biomechanical, and physical performance effects of three extremity armor systems designed to be worn with and to augment the torso protection provided by a tactical armor vest. The effort was funded by the US Marine Corps Warfighting Laboratory under a project entitled “Natick Soldier Center Engineering Support for Biomechanical, Physiological, Human Performance, and Area Coverage Analysis of Extremity Body Armor Systems” (MIPR #M9545006MPR6CC7).

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Special recognition is due to the study volunteers, who were enlisted men assigned to Headquarters Research and Development Detachment, NSRDEC, Natick, MA.

EXECUTIVE SUMMARY

The US Marine Corps and the US Army have been engaged in efforts to evaluate improved body armor for the Soldier and the Marine, including armor to protect the extremities. These efforts are focused on both body armor performance (i.e., ballistic protection) and armor effects on the physical performance of personnel (e.g., body flexibility, mobility, and agility).

The purpose of this investigation, which was conducted by the Natick Soldier Research, Development and Engineering Center between February 2007 and May 2008, was to provide an evaluation of the physiological, biomechanical, and physical performance effects of three extremity armor systems: the Integrated Dismounted Armor System™ (IDAS), Deltoid Protector/Lower Extremity Body Armor (DP/LEBA), and QuadGuard. Each of these systems weighed approximately 6 kg and was designed to be worn with and to augment the torso protection provided by a tactical armor vest. In this investigation, the extremity armor systems were tested with the Interceptor Multi-Threat Body Armor (IBA), which consists of the Outer Tactical Vest, collar, groin protector, and front and back Small Arms Protective Inserts. The IBA was also tested without any extremity armor as a baseline condition. The effects of these conditions on energy consumed during walking and running and on walking and running movement patterns were analyzed. Additional physical performance measures involving militarily relevant tasks requiring mobility and agility (repetitive box lift, grenade throws, 30-m rushes, and obstacle course runs) were recorded under the armor conditions tested, as were assessments of range of motion and the evaluation of human factors issues associated with armor wear. Three-dimensional body surface scans were also included for each condition tested in order to acquire data on the surface area covered by ballistic-protective material.

The findings from this study indicate that, compared with wearing only the IBA, use of extremity armor increases the energy consumed during walking and running, changes the biomechanics of gait, increases the ground reaction forces (GRFs) associated with locomotion, and negatively affects performance of some militarily relevant physical tasks. Statistically significant differences were obtained between the IBA alone and the IBA plus extremity armor on a number of objective measures taken in this study. These differences were attributable to the weight of the extremity armor. Extremity armor weight resulted in longer times to complete physically demanding activities requiring speed of movement. The weight also resulted in increased energy usage and higher magnitude GRFs during walking and running.

The three types of extremity armor tested were highly similar to each other in weight, but there were design variations that yielded differences among the three systems on some of the performance measures. One aspect of design in which the systems differed was body surface area covered by ballistic-protective material. The QuadGuard, which had the greatest area coverage, encumbered movement of the lower extremities and was selected by study volunteers as the extremity armor they least preferred. Based on overall results of testing, performance with the QuadGuard differed from that with the IBA alone to a somewhat greater extent than performance with the other two extremity armor systems did. The IDAS had the least area coverage, and it was selected by study volunteers as their most preferred extremity armor system. Overall results with the IDAS were somewhat more positive than those with the QuadGuard and similar to those with the DP/LEBA.

The study volunteers definitely viewed the QuadGuard least favorably and the IDAS most favorably of the three extremity armor systems. The objective measures taken in this testing, however, did not reveal extensive differences among the systems. From the results on the objective measures, there is no basis to recommend any one of the three systems over the others for future military use. The systems were not, however, tested for the thermal burden they impose on the user. The systems may well differ in this regard due to differences in their area coverage.

AN INVESTIGATION OF THREE EXTREMITY ARMOR SYSTEMS: DETERMINATION OF PHYSIOLOGICAL, BIOMECHANICAL, AND PHYSICAL PERFORMANCE EFFECTS AND QUANTIFICATION OF BODY AREA COVERAGE

INTRODUCTION

This report documents a study of three extremity armor systems conducted by the Natick Soldier Research, Development and Engineering Center (NSRDEC) between February 2007 and May 2008. Components providing ballistic coverage of the upper and lower arms and the upper and lower legs were included in the study. From the data acquired, comparisons were made of the relative effects on performance of the three systems. The Interceptor Multi-Threat Body Armor (IBA), which consists of the Outer Tactical Vest (OTV), collar, groin protector, and front and back Small Arms Protective Insert (SAPI) plates, was used with the extremity armor throughout the study. Testing was also conducted with the IBA alone in order to assess the impact of extending ballistic protection to the extremities compared with protection of the torso only. In addition, 3-dimensional (3D) scanning was carried out on study participants outfitted in each armor condition being investigated in order to acquire data on coverage of the body surface provided by the various armor conditions.

The purpose of this evaluation was to assess the physiological, biomechanical, and performance effects of the three extremity armor systems relative to each other and to a condition in which no extremity armor was worn. The effects of these conditions on walking and running movement patterns and the energy consumed in walking and running were analyzed. Additional physical performance measures involving militarily relevant tasks requiring mobility and agility (repetitive box lift, grenade throws, 30-m rushes, obstacle course run) were also included, along with assessments of range of motion, evaluation of human factors issues associated with armor wear, and determination of armor coverage through 3D scans of the body surface.

The current battlefields require a highly mobile, rapidly deployable ground force that will face increasingly sophisticated weaponry in diverse environments. The lethality of these environments requires members of the armed forces to wear protective gear that will provide a balance between protection and functionality. Soldiers and Marines deployed to Iraq and Afghanistan currently wear a tactical armor vest to protect the torso against shrapnel and hand gun rounds. Small arms inserts are added to protect the torso against rifle ammunition. Tactical armor vests are effective and highly valued pieces of equipment and have saved many lives. Injury statistics compiled on all US service members who received treatment for combat wounds sustained in Iraq or Afghanistan from 2001 through 2005 indicate that just 6% of the wounds were to the thorax (Owens et al., 2008).

Whereas data compiled in Iraq and Afghanistan indicate that the proportion of wounds to the torso areas protected by armor vests was quite low, the proportion of wounds to the extremities was relatively high, at 54% (Owens et al., 2008). It has been reported that injuries to the extremities are proving difficult to manage surgically, as they often combine severe soft tissue, bone, and vascular wounds (Greer, Miklos-Essenberg, & Harrison-Weaver, 2006). The

US Army and the US Marine Corps are interested in utilizing extremity armor to aid in prevention of these injuries. A major disadvantage of extremity armor coverage is the weight the armor adds to the extremities, which may result in a negative impact on the performance of the Soldier and the Marine. The use of extremity armor systems by the Soldier and the Marine must be evaluated to quantify the extent to which the systems impede an individual's ability to perform essential military tasks, increase energy usage, and tax the cardiovascular system. The physiological and biomechanical effects of extremity armor weight and coverage distribution on the limbs must be evaluated to determine the cost/benefit ratio for Soldier performance to level of protection. In this study, three extremity armor systems were evaluated in terms of their relative effects on the wearer's physical performance.

Overview of Military Body Armor

Armor to provide ballistic protection of the torso was first used by dismounted US Army and Marine personnel during the Korean conflict. Armor vests were issued to ground troops on a wider scale during the Vietnam War. The vest used in Vietnam, the M-1959 Fragmentation Protective Body Armor, had a filler made of ballistic nylon, which was sealed in a waterproof, vinyl envelope. As the name indicates, the vest provided protection against munition fragments. Feedback from users in Vietnam indicated that the vests were hot and heavy and interfered with performance of military operations. For these reasons, some personnel did not wear the vests on a regular basis. On the other hand, there was strong evidence of the effectiveness of the armor vests, in terms of decreased casualty rates and decreased wound severity, among troops who did use the vests (Haisman & Crotty, 1975).

Since the Vietnam era, other armor vests have been developed for US ground troops. One was the Personnel Armor System for Ground Troops (PASGT) vest. The PASGT was soft armor that incorporated plies of water-repellant treated Kevlar®, an aramid material that was not yet available when the M-1959 vest was being developed. (Aramids are heat- and cut-resistant polymeric fibers with a carbon backbone.) The PASGT provided about the same body area coverage of the torso as the M-1959. That is, it extended from the shoulders to about waist level, covered the tops of the shoulders, and had an attached 3/4 stand-up collar. The PASGT vest was designed to provide better fragmentation protection than the M-1959. Through use of the advanced materials, improved protection was achieved without an increase in weight. In a size medium, the PASGT and the M-1959 both weighed approximately 4 kg.

The selection of materials for the PASGT resulted in a vest that was thinner and more flexible than the M-1959. Design features were also implemented in the PASGT vest with the goal of improving user mobility. Studies conducted to compare Soldiers' performance in the two vests found that the PASGT was generally superior to the M-1959 with regard to range of body motion, ability to properly shoulder a rifle, and speed of execution of arm/hand coordination tasks (Bensel, Fink, & Mellian, 1980; Corona, Jones, Randall, Ellis, & Bruno, 1974). Study participants preferred the PASGT, citing better balance on the torso, less restriction of movement, and greater comfort. Although the PASGT and the M-1959 vests were approximately equal in weight, participants also reported that the PASGT felt lighter than the M-1959 (Bensel et al.; Corona et al.). The PASGT was adopted as a replacement for the M-1959 vest, and issue of the vest to Soldiers and Marines was begun in the early 1980s.

In 1996, an item was fielded to augment the protection provided by the PASGT vest when battlefield conditions warranted. It consisted of shoulder straps with two cloth panels attached. A panel covered a portion of the front or the back of the upper torso. The panels were designed as large pockets. Each served as a carrier for hard armor: a ceramic plate. The plates were developed to provide protection against small arms. The weight of the added small arms protection was about 7.4 kg.

The PASGT vest and the augmentation for small arms protection were phased out of the military supply system, and the IBA, a system developed in the late 1990s, was introduced. The IBA has a number of components. A major component is the vest, the OTV. Like the PASGT, the OTV is soft armor. The OTV provides about the same area coverage of the torso as the PASGT and the Vietnam-era M-1959. Like the earlier vests, the OTV covers the tops of the shoulders and has a collar. The collar on the OTV can be removed and reattached by the user, unlike the collar on the PASGT, which was permanently attached to the body of the vest. The ballistic-protective material in the OTV is a Kevlar weave. By incorporating new materials, greater ballistic protection was achieved at a lighter weight in the OTV, compared with the PASGT. The OTV provides increased protection against fragments. In a size medium, the OTV with its collar attached has a nominal weight of 3.5 kg, or about 15% less than a PASGT.

The OTV is the foundation of the IBA system. Another system component is a groin protector that attaches to the lower portion of the vest and, like the collar, can be removed and reattached by the user. The groin protector weighs 0.4 kg. The IBA with the collar and groin protector attached is pictured in Figure 1.

Figure 1. IBA with collar and groin protector attached.

Integral to the front and the back of the OTV are two large pockets. Each pocket is dimensioned to accommodate hard armor in the form of a removable boron carbide ceramic plate, the SAPI. As is the case with the OTV, the SAPI plates incorporate advanced materials to achieve greater ballistic protection and a reduction in weight, compared with the plates in the small arms protection provided for use with the PASGT vest. The SAPI plates are designed to protect against rifle and machine gun fire. A pair of SAPI plates in a size medium weighs 3.6 kg, a 50% weight reduction relative to the small arms protection provided for the PASGT.

The IBA with all its components, including the SAPI plates, has been widely used in Afghanistan and Iraq. Troops have reported many instances in which the vest defeated ballistic

threats and saved lives. The system is also well-regarded from the perspective of compatibility with military operations. Results of questionnaires administered to military serving in Iraq indicated that over 80% of the respondents did not feel that the IBA interfered with execution of mission-related tasks (Greene, 2005). Further, in controlled testing done on rifle-firing accuracy, it was found that, for targets between 50 and 150 m, the probability of a hit was higher with the IBA than when armor was not worn. The advantage of using the IBA diminished somewhat at 200 m and beyond to approximate accuracy without the vest (Kramlich, 2005).

From the time of the Korean War, when body armor for ground troops was first introduced, to the present, great improvements have been made in the ballistic protection afforded to Soldiers and Marines in the face of evolving types of munitions, and this has been achieved while reducing armor weight and increasing compatibility of the armor with the mission-related tasks that dismounted troops must carry out. What has remained essentially unchanged in the armor used over these years is the portion of the body covered by ballistic-protective materials. However, because of the battlefield threats being encountered by Soldiers and Marines serving in Iraq and Afghanistan, the Army and the Marine Corps launched initiatives to increase the body area coverage to include the arms and the legs. A study of the physiological, biomechanical, and physical performance effects of extremity armor on military personnel is documented in this report.

Extremity Armor

The three extremity armor systems that were tested in this study are described in the following sections.

Integrated Dismounted Armor System

The Integrated Dismounted Armor System (IDAS™) was a modular extremity-protection system designed for mounted or dismounted operations by Allen-Vanguard Technologies, Inc. (Ottawa, Canada). The IDAS was developed to protect against munition fragments. Components included a jacket, trousers, arms, kneepads, and lower leg attachments. The IDAS was designed to be worn under the IBA and could be used in a basic configuration or a full configuration. In the basic configuration, ballistic-protective pieces were worn on the upper arms and the upper legs. In the full configuration, ballistic-protective pieces were added to cover the lower arms and the lower legs. The upper and lower arm pieces were secured to each other by straps having hook-and-pile fastener tape; the same scheme was used to secure the upper and lower leg pieces. The IDAS is pictured in Figure 2.

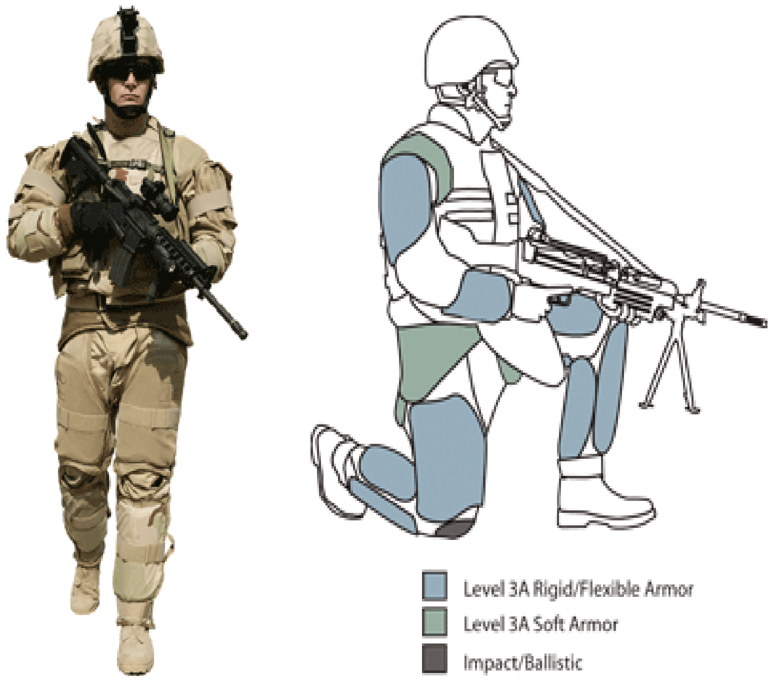


Figure 2. IDAS.

Deltoid Protector/Lower Extremity Body Armor

The Deltoid Protector (DP) and the Lower Extremity Body Armor (LEBA) were developed by NSRDEC. The DP attached to the shoulder of the OTV and provided the same level of ballistic protection as the OTV. The DP covered the upper arm (Figure 3). There was no companion piece to cover the lower arm. The LEBA was comprised of nine component parts (Figure 3). These were: a ballistic-protective belt, a groin protector, two thigh protectors, two (nonballistic) kneepads, two lower leg protectors, and suspenders. The LEBA was worn with the IBA. The LEBA was intended to be used by mounted and dismounted personnel. Each of the ballistic-protective components of the LEBA system could be used with either one or two ballistic-protective inserts at the user's discretion. Webbing attachments on the LEBA belt and thigh-protection assemblies were compatible with Modular Lightweight Load Carrying Equipment (MOLLE) attachments. The attachments on the LEBA were provided to accommodate the carrying of a few items.

Figure 3. DP and LEBA

QuadGuard

QuadGuard was soft armor for the extremities, which was researched and developed at Oklahoma State University, Stillwater. The ballistic material in the armor was Dyneema®, a polyethylene fiber. QuadGuard, pictured in Figure 4, was designed to protect against munition fragments and was worn with the IBA. The system consisted of two arm pieces, which attached to the OTV, and a set of trousers that covered each leg and were connected by a waist belt. The upper and lower sections of the arms zipped together in the area of the elbow. Similarly, the upper and lower sections of the trouser legs zipped together at about knee level. The user had the option of wearing only the upper arm and leg sections or wearing the complete system. The QuadGuard system was developed for use by vehicle crews, breaching parties in urban operations, and security and support units.

Figure 4. QuadGuard.

Effects of Armor Vests on Physical Performance

The research into the effects of body armor on aspects of performance germane to tactical operations of military ground troops is not extensive. Further, most of the studies that have been done involve some form or variation of an armor vest, but not armor to protect the extremities. Thermal stress imposed by vest wear has been the focus of a number of the investigations (Larsen, Netto, & Aisbett, 2011).

Armor vests normally cover approximately 30 to 35% of the body surface area (van de Linde & Lotens, 1988). Depending upon ambient temperature, humidity, solar load, wind speed, and physical work intensity, the added insulation of the vest and its resistance to evaporative cooling can lead to heat strain (Cadarette, Blanchard, Staab, Kolka, & Sawka, 2001; Cheuvront, Goodman, Kenefick, Montain, & Sawka, 2008; Haisman & Goldman, 1974; McLellan et al., 2003; Yarger, Cronau, & Goldman, 1968; Yarger, Litt, & Goldman, 1969). Cadarette, Matthew, and Sawka (2005) found that, during moderate, continuous work (425 W) in environments allowing some evaporative cooling [40 °C, 20% relative humidity (RH), 27.8 °C wet-bulb globe temperature (WBGT)], equilibrium body core temperatures of individuals wearing a regular field uniform alone were about the same as those of individuals wearing an armor vest over the uniform. However, in an uncompensable hot environment (32.2-37.8 °C, 75% RH, 32.2-35.0 °C WBGT), a decrease in WBGT of about 2.8 °C was required for equilibrium body core temperatures of individuals wearing body armor to be the same as those individuals wearing only a field uniform. Depending upon ambient environmental conditions and work intensity, wearing an armor vest can also increase an individual’s daily water need by an additional 0.5 to 2.0 qt per day because of increased sweat rate (Montain & Stamm, 2000).

Like Cadarette et al. (2005), Cheuvront et al. (2008) studied individuals exercising in a regular field uniform alone and wearing an armor vest over the uniform. The vest used by Cheuvront et al. was the IBA with front and back SAPI plates. Eleven men exercised in a hot-dry environment (35 °C, 30% RH) for a total of 4 h, with each hour consisting of 50 min of walking on a treadmill and 10 min of resting. When the uniform only was being tested, walking speed was set at $1.56\ m \cdot s^{-1}$, and the treadmill grade was 3%. For testing of the vest, walking speed was

again 1.56 $m \cdot s^{-1}$, but the grade was set at 2% in order to compensate for the added weight of the vest. Cheuvront et al. found that heart rate was higher with than without the vest and that the difference in heart rate between the two conditions increased with hours of walking, from an average of 7 $beats \cdot min^{-1}$ higher with the vest after 1 h to an average of 19 $beats \cdot min^{-1}$ higher by the end of the fourth hour. They concluded that the IBA increased physiological strain independent of the added weight that it imposed on the body.

In addition to research into the thermal implications of wear of armor vests, there are several studies in which effects of vests on ranges of body motion were examined. These studies were done to compare candidate designs or new materials in terms of relative restrictions on planar movements of the body, and they included conditions in which participants were tested without protective vests (Bensel et al., 1980; Woods, Polcyn, O'Hearn, Rosenstein, & Bensel, 1997). It was found that, compared to the extent of movement without a vest, use of armor vests can restrict flexion and rotation of the head, flexion at the waist, and extension and abduction of the upper arm. Not unexpectedly, given that armor vests cover the torso from shoulder to about waist level, the studies indicate that flexion and abduction of the upper leg are not generally limited by use of a vest (Bensel et al.; Woods et al.).

Effects of armor vest wear on simple physical activities have been investigated, as well. Ricciardi, Deuster, and Talbot (2008) conducted a study of such activities as affected by an armor vest weighing approximately 10 kg and found performance of the activities to be markedly impaired when the vest was worn. Male military personnel performed as many pull-ups as possible with and without the vest. The average number of repetitions was 61% lower when the vest was worn. Female military personnel were also tested. The length of time they could hang from a pull-up bar, keeping the arms flexed and the chin over the bar, was recorded. Average hang time was 63% lower with the vest than without it. On a stair-step test performed by both the men and the women, the average number of steps climbed was lower, by 16%, with the vest.

The temporal and kinematic characteristics of a dynamic, repetitive motion have also been examined for armor vest effects. This work was conducted by Martin and Nelson (1982, 1986), who captured and analyzed the movements of men and women walking on a level surface at an experimenter-determined speed of 1.78 $m \cdot s^{-1}$ while dressed in a number of outfits that varied in the items worn and in weight. A minimal clothing/minimal weight condition consisted of a T-shirt, shorts, and sneakers (~0.7 kg). A second condition consisted of a field uniform, combat boots, and a fighting load (~9.2 kg). To this was added a helmet and an armor vest to obtain a third condition (~17.0 kg). Analyses of stride variables revealed that stride length, single leg contact time, and double support time when the armor was used did not differ significantly from the minimal clothing condition. However, stride rate (in $strides \cdot s^{-1}$) was significantly higher and swing time was significantly shorter for the armor vest than for the other two conditions. Martin and Nelson ascribed the differences in gait to the variations in the magnitudes of the external load on the body.

Physiological Effects of Adding External Loads to the Torso

Although the research into the effects of body armor, *per se*, on performance is limited, a large amount of research has been completed on evaluating the effects of added load on the body

(Knapik, Harman, & Reynolds, 1996). Much of this work addresses issues related to the energy consumed carrying weighted backpacks, with energy utilization quantified by taking measurements of the rate of oxygen uptake ($\dot{V}O_2$) during performance of physical activities. In studies done on marching with backpack loads, it has been found that energy consumption increases with increases in the mass of the load and the speed of walking (Pandolf, Givoni, & Goldman, 1977; Polcyn et al., 2002; Sagiv, Ben-Sira, Sagiv, Werber, & Rotstein, 1994; Soule, Pandolf, & Goldman, 1978).

Few studies have been done on the energy consumed while walking with and without body armor, and that research has involved armor vests, but not extremity armor. Ricciardi et al. (2008) measured the $\dot{V}O_2$ of 17 military men and 17 military women walking on a treadmill with and without an armor vest weighing approximately 10 kg. After a brief warm-up, the men were to walk for 10 min at a speed of 1.07 $m \cdot s^{-1}$ on a 5% grade, followed by a 10-min period at 1.70 $m \cdot s^{-1}$ on a 10% grade. The same experimental protocol was employed for the women, but they were to walk at slightly slower speeds at each grade (i.e., 1.03 and 1.61 $m \cdot s^{-1}$ at the 5 and the 10% grades, respectively). Average $\dot{V}O_2$, calculated over the data of the men and the women, was 12% higher with the vest at the lower grade and 17% higher at the higher grade. Further, at the 10% grade, seven men and seven women were unable to complete the 10 min of walking while wearing the vest and three men and three women did not complete the 10-min walking period without the vest. The reasons Ricciardi et al. cited for the early termination were volitional fatigue, achieving the maximum rate of oxygen uptake, and limiting dyspnea. All participants completed the 10 min of testing at the 5% grade, regardless of whether they were wearing the armor vest.

In another study in which $\dot{V}O_2$ was measured during walking, Legg and Mahanty (1985) investigated various means of carrying a load on the torso, and included a British Army fragmentation-protective vest and an unloaded condition. A backpack with a frame and a double pack were also tested. The double pack consisted of a pack worn on the back and a small pack located on the chest. Legg and Mahanty measured the $\dot{V}O_2$ of men walking on a level treadmill set at a speed of 1.25 $m \cdot s^{-1}$ while carrying 35% of their body weight. Load mass was comprised of the mass of the carrying device plus sandbags. For the armor vest, sandbags were placed in pockets around the waist to augment the weight of the vest itself and bring the total mass to 35% of body weight. The findings indicated that the energy consumed when walking in the loaded vest was approximately equal to the energy consumed when walking with the backpack and with the double pack. All these means of carrying the load increased $\dot{V}O_2$ relative to the unloaded condition by about 30 to 35%.

Physiological Effects of Adding External Loads to the Extremities

As has been mentioned, the research done to quantify the effects of body armor on performance is limited, and armor vests, not ballistic-protective items for the extremities, have been the focus of the work that has been undertaken. However, some information on the possible effects of extremity armor on performance may be gleaned from studies in which loads have been placed on the upper and the lower extremities.

Upper Extremity Weighting

The effects of loads added to the upper extremities on $\dot{V}O_2$ during walking and running have been researched and it has been shown that adding weight to the upper extremities is not as efficient in terms of energy usage as adding weight to the torso. Soule and Goldman (1969) found that energy consumption during walking with a given mass on the hands is about two times greater than the energy consumed during walking with the same mass on the torso. Miller and Stamford (1987) reported a 1.3% increase in energy consumption per 100 g of added weight to the hands. Weighting the upper extremities at the hands as compared to the wrists also demonstrated a difference in energy consumption. $\dot{V}O_2$ and heart rate responses were significantly greater for hand-held weights when compared to wrist weights, and the responses were greater for both weighted conditions than for a nonweighted condition (Graves, Martin, Miltenberger, & Pollock, 1988).

Lower Extremity Weighting

A number of investigators have reported that the energy consumed when walking with a given mass on the feet is four to six times greater than the energy usage when walking with the same mass on the torso (Catlin & Dressendorfer, 1979; Holewijn, Heus, & Wammes, 1992; Jones, Knapik, Daniels, & Toner, 1986; Jones, Toner, Daniels, & Knapik, 1984; Legg & Mahanty, 1986; Soule & Goldman, 1969). Research results also indicate that increases in footwear weight substantially increase energy usage during walking. The findings are in general agreement that there is a 0.7 to 1.0% increase in energy used per 100 g of added weight to the feet (Catlin & Dressendorfer; Jones et al., 1986; Legg & Mahanty; Martin, 1985; Miller & Stamford, 1987). Loading the lower extremities during running has similar physiological effects to those associated with walking (Claremont & Hall, 1988; Martin, 1985).

Martin (1985) contrasted additional loads on the feet with additional loads on the thighs during running. He found that adding 0.5 kg to each foot increased $\dot{V}O_2$ by 7.2%, which was nearly twice the increase due to adding the same mass to the thighs. A kinematic analysis also demonstrated that a 0.5-kg load added to each foot produced small but significant increases in stride length, swing time, and flight time and a decrease in peak ankle velocity (Martin). Hence, energy usage is not only affected by adding mass to the limb, but it can also be affected by the distribution of that mass.

Distribution of mass on the leg was investigated further by Royer and Martin (2005). They examined the effects of manipulating leg mass and moment of inertia (MOI) independently on energy consumption and electrical activity of the leg muscles during walking. A mean total load of 5.64 kg was distributed on the proximal and distal portions of both lower legs and on the torso in three different ways to result in three different limb inertial characteristic conditions. For a baseline condition, the load was distributed on the lower extremities and the hips. In a large MOI condition, MOI about the transverse axis of the hip was increased 5% from the baseline condition while sustaining the baseline lower-extremity mass. In a large mass condition, total lower-extremity mass was increased by 5% relative to the baseline condition while sustaining the baseline MOI about the hip. Participants were tested for 6 min on a treadmill set at a walking speed of $1.5\ m \cdot s^{-1}$. Average $\dot{V}O_2$ was computed for the last 2 min. Royer and Martin found that

the increase in energy consumption relative to the baseline was about the same for the large MOI and the large mass conditions (3.4% for the MOI condition and 4.0% for the mass condition). Despite the increases in energy consumption, there were few statistically significant differences among the loading conditions in peak amplitude of muscle activity. Thus, there was no evidence on which to conclude that the increased energy consumption with the leg loading schemes was attributable to increased demand on leg muscles.

Physical Performance Tests Used to Assess Extremity Armor in the Current Study

A number of objective tests were used in the present study in order to acquire data on physical performance as affected by wearing extremity armor. The performance tests included those applied in past research on armor vests and those used in studies to assess the effects of adding loads to the extremities (Bensel et al., 1980; Legg & Mahanty, 1985; Martin, 1985; Martin & Nelson, 1982, 1986; Royer & Martin, 2005; Soule & Goldman, 1969; Woods et al., 1997). Specifically, body range of motion was measured and metabolic and biomechanical responses during walking and running were captured and analyzed. Additional tests were used that were selected for their military relevance, strong agility and maneuverability components, and involvement of the upper extremities, as well as the lower extremities. These tests were a repetitive box lift test, a grenade throw for distance and accuracy, a series of 30-m combat rushes, and an obstacle course run.

A maximal-effort, timed, repetitive lifting test was established previously to simulate the resupply of a 155-mm self-propelled howitzer (Sharp, Harman, Boutilier, Bovee, & Kraemer, 1993). The score taken on the test is the maximum number of weighted boxes lifted to a 132-cm high shelf in a 10-min period. The box lift task has been used to assess the efficacy of various physical training programs by comparing the number of lifts accomplished before and after training (Harman et al., 1997; Knapik & Sharp, 1998; Sharp, Bovee, Boutilier, Harman, & Kraemer, 1989; Sharp & Legg, 1988). Similar protocols have been employed to examine the repetitive lifting capacity of women before and after progressive resistance training programs (Harman et al, 1997; Knapik & Gerber, 1996; Kraemer et al., 2001). Pandorf et al. (2003) reported that the box lift task is a reliable occupational physical performance test (intraclass correlation coefficients of .92-.94). However, at least one practice trial of the box lift task is required before highly reliable performance data are obtained.

The test of grenade throwing distance and accuracy used in the current study is based on an Army training activity. According to Army guidance, a Soldier should be able to throw a hand grenade to within 5 m of a selected point 30 m away (US Department of the Army, 2008). Grenade throwing distance and accuracy have been tested in studies of various designs of load-carriage equipment (Harman et al., 1999b; Obusek & Bensel, 1997). Decreases in the distance thrown and increases in distance from the target center were obtained when a fighting load was worn, compared to when there was no load on the body. Researchers attributed these findings to the restriction imposed on the arm-shoulder girdle by the fighting load (Harman et al.; Obusek & Bensel). Harper, Knapik, and de Pontbriand (1997) reported the use of a grenade throw as a test of upper body power immediately following a 10-km road march on which Soldiers used backpacks and carried military loads of 18 to 36 kg. The mean distance of the grenade throw

decreased after the march, compared with premarch test scores. The greatest decrease was after marching with the heaviest load. Harper et al. proposed that decrements in grenade throw performance may have been due to local fatigue of back and shoulder muscles or to compression of the brachial plexus by the shoulder straps of the backpack.

As is the case with handling hand grenades, the combat rush used in the current study is a basic activity Soldiers are trained to perform that has been adapted as an objective performance test (US Department of the Army, 2011). Soldiers use the rush to move from one covered, protected location to another. The rush involves moving from a prone to a standing position, running, and moving from a standing position to return to a prone position. Soldiers repeat the actions of the rush sequence as they move forward. The time spent in a standing and running position is limited to 3 to 5 s to avoid enemy fire. Harman, Frykman, Gutekunst, & Nindl (2006) developed a timed test based on the rush. The test consists of rising from a prone position, running 30 m, and returning to a prone position. This cycle is repeated until five 30-m rushes have been completed. The time for each rush and total time for the task are recorded. Treloar and Billing (2011) had male and female Soldiers complete five 30-m rushes when the Soldiers were outfitted in a duty uniform only and when they also wore a fighting load weighing 21.6 kg. Compared with the uniform only, mean sprint time was slower by about 32% when the components of the fighting load were worn. In addition to measuring time to complete each 30-m rush, Treloar and Billing measured split times at 5-, 10-, 15-, 20-, and 30-m intervals. Analyses of these data revealed that the greatest difference between the control and the fighting load conditions occurred during the 0- to 5-m portion of the sprint, the portion during which the Soldiers had to rise from a prone position and initiate the sprint.

Times to complete an obstacle course, which was set up in a laboratory, were recorded in the current study. Obstacle courses typically entail such activities as running, jumping, crawling, climbing, and balancing. Courses have been used extensively in studies to evaluate different designs of load-carriage equipment (Brainerd & Bruno, 1985; Bryant et al., 2004; Frykman, Harman, & Pandorf, 2001; Harman et al., 1999a, 1999b; LaFiandra et al., 2003). Frykman et al. investigated obstacle course completion times of female Soldiers under two load weight conditions. The women were tested in a fighting load of 14 kg and in a condition weighing 27 kg, which consisted of the fighting load plus a backpack weighted to 13 kg. Frykman et al. reported that the women required from 12% to 26% longer to complete the course with the heavier load. LaFiandra et al. also tested load-carriage gear on an obstacle course. The items tested were external-frame and internal-frame backpacks loaded to the same weight, about 21 kg. Male Soldiers served as study participants. The Soldiers completed an obstacle course immediately before and after 3.2-km marches with the backpacks. No differences in course times were obtained between backpack designs, but times on the course were significantly longer after the march. Kirk et al. (2007) used an obstacle course in a study of backpacks varying in weight and in carrying capacity. They found that course completion times were sensitive not only to differences in weight on the body, but also to backpack volume.

METHOD

Study Participants

Participants were 11 US Army enlisted men recruited from among the military personnel who serve as human research volunteers assigned to Headquarters Research and Development Detachment, NSRDEC. Ten of the men (MOS 11B, infantryman) had just completed Advanced Individual Training and their mean time in service was 5 months. One man (MOS 19K, armor crewman) had time in service of 20 months. These volunteers were asked to participate after being informed of the purpose of the study, the nature of the test conditions, the risks associated with the study, all procedures affecting a volunteer's well-being, and a volunteer's right to discontinue participation at any time without penalty. Those who agreed to participate in the study expressed their understanding by signing a volunteer consent form. The study was approved by the local Institutional Review Board and conducted in accordance with Federal Policy for the Protection of Human Subjects, US Department of Defense, 32 Code of Federal Regulations (CFR) Part 219.

Prior to participation in the study, all volunteers underwent medical screening, including a physical examination and clinical review of their medical records, with an emphasis on the musculoskeletal system. Individuals with a history of back problems, including herniated intervertebral discs or previous orthopedic injuries that limited the range of motion about the shoulder, hip, knee, or ankle joint, were excluded from participation. Volunteers abstained from heavy or moderate exercise and alcohol consumption 24 h prior to each day of testing. Summary statistics of the physical characteristics of the men are presented in Table 1.

Table 1. *Demographics of Study Participants (N = 11)*

Variable	Mean	Minimum	Maximum
Age (years)	20.0	18.7	22.5
Stature (m)	1.8	1.7	1.9
Weight (kg)	79.7	62.2	92.2

Study Design

Overview

Volunteers attended 10 sessions of 2.5 h to 4 h each, depending on study activities scheduled for that session. The activities that were carried out by a volunteer during the study and the principal measures taken in conjunction with the activities were:

- Energy usage and biomechanical responses to treadmill walking for approximately 10 min on a 0% grade at a speed of 1.34 $m \cdot s^{-1}$
- Energy usage and biomechanical responses to treadmill running for approximately 10 min on a 0% grade at a speed of 2.24 $m \cdot s^{-1}$
- Box lift and carry cycles completed in 5 min

- Distance and accuracy of grenade throws
- 30-m rush completion times
- Obstacle course run times
- Range of motion measurement and assessment of human factors issues
- 3D body scanning for surface area coverage of armor systems

Each volunteer was tested in each of four armor conditions. Prior to the start of testing, the orders in which the volunteers were exposed to the conditions were determined to avoid bias and confounding in the data.

All treadmill, box lift, obstacle course, and human factors testing was conducted at the Center for Military Biomechanics Research, Soldier Systems Center, Natick, MA. The grenade throw was conducted at the Soldier System Center's softball field, and the 3D scanning was completed in the Anthropometry Laboratory, Soldier Systems Center.

Armor Conditions

Each volunteer was tested in four armor conditions. All conditions entailed wearing of the IBA (Figure 1). Throughout the study, the following components were worn to comprise the IBA: OTV, collar, groin protector, and two SAPI plates (one front and one back plate). Volunteers were tested in the IBA alone and in the IBA plus extremity armor. Three extremity armor systems were included: the IDAS, the DP/LEBA, and the QuadGuard. These are pictured in Figures 2, 3, and 4, respectively. The weights of the armor conditions are presented in Table 2.

The basic clothing worn by the volunteers, aside from the armor, varied with the activity being tested. For treadmill walking and running, volunteers wore a helmet, spandex shorts, a T-shirt, socks, and broken-in combat boots. They also carried a simulated M-4 carbine in the "ready" position. For the 3D body scanning, spandex shorts and a wig cap were used. For the remaining activities, volunteers wore the field duty uniform, T-shirts, socks, and combat boots. The volunteers wore their own uniforms and broken-in boots. The investigators supplied the other items.

The following comprise the armor conditions that were tested in the study:

1. IBA, consisting of OTV, collar, groin protector, and two SAPI plates, worn with the basic clothing (IBA condition)
2. IDAS upper and lower arm and upper and lower leg components, worn with the IBA and the basic clothing (IDAS condition)
3. DP/LEBA upper arm and upper and lower leg components, worn with the IBA and the basic clothing (DP/LEBA condition). This system does not have a lower arm component.
4. QuadGuard upper and lower arm and upper and lower leg components, worn with the IBA and the basic clothing (QuadGuard condition)

Table 2. *Weight of the Armor Conditions*

Item	Weight (kg)
1. IBA (including neck collar, groin protector, SAPI plates) + Basic Clothing (shorts or uniform, boots, helmet, and simulated M-4 carbine)	14.80
2. IDAS + IBA + Basic Clothing	20.45
3. DP/LEBA + IBA + Basic Clothing	21.25
4. QuadGuard + IBA + Basic Clothing	20.36

The order in which volunteers were tested under the four conditions was determined by establishing 11 testing sequence schemes, one for each volunteer, for each activity prior to the beginning of the study. For a given activity, each volunteer was randomly assigned to one of the schemes. The testing sequence schemes were based on a Latin Square approach. Two constraints were applied in establishing the sequence schemes: 1) for a given study activity, no two volunteers had the same order of testing of armor conditions; and 2) a given volunteer had a different order of testing of armor conditions at each activity.

Procedure

The methods employed in the study for carrying out each of the test activities are described below. Volunteers may have completed more than one of the test activities at a single session. Similarly, there may have been practice on one activity and testing on another within a session.

Physiological and Biomechanical Analyses of Treadmill Walking and Running

Equipment and Measurements

Force plate treadmill. For testing during treadmill walking and running, a force plate treadmill, fabricated by AMTI (Watertown, MA), was used. This treadmill is comprised of two synchronized treadmill belts, located one in front of the other. The belts are very close together, with a gap of less than 10 mm in the direction of motion (anterior-posterior or fore-aft). The motors for the belts are synchronized and feedback-controlled so that, if the speed of one belt changes, the other belt maintains an identical speed. The treadmill can attain speeds of up to 4.83 $m \cdot s^{-1}$ and can be set at grades of ± 25%.

Each of the two belts is mounted over a force plate, which is capable of measuring ground reaction force (GRF) in three planes. Each force plate in the treadmill provides six continuous voltage output signals corresponding to forces and torques in three orthogonal directions (x, y, z). For this study, the voltage outputs of the force plates were sampled at the rate of 1200 Hz, filtered with a low-pass Butterworth filter (cut-off frequency of 10 Hz), and converted to physical units (N) using manufacturer-supplied calibration factors. The digital values were stored in computer data files. A number of kinetic variables were derived from the

GRF-time histories and analyzed to assess the effects of the armor conditions on walking and running. The variables included peak vertical, braking, and propulsive forces.

Motion capture equipment. Three-dimensional motion was recorded by ProReflex Motion Capture Unit (MCU) cameras (Qualisys AB, Gothenburg, Sweden) as the volunteers walked or ran on the treadmill. These data were used to analyze gait kinematics. Retro-reflective markers, about 12 mm in diameter, were placed at selected locations on the volunteer's skin and clothing to expedite processing of the gait kinematics. To capture the volunteer's movements on the treadmill, eight cameras, operating at 120 Hz, were focused on the area of the treadmill. The cameras were positioned on each side and anterior and posterior to the viewing area. This allowed the kinematics of the whole body to be defined in 3D space with 6 degrees of freedom biomechanical movement analysis for each body segment. The outputs of the cameras and the force plates were collected through a single data acquisition system and were time-synchronized.

The recorded images were processed using dedicated hardware and software (Qualisys AB, Gothenburg, Sweden) to produce files containing time histories of the 3D coordinates of each reflective marker. The Visual3D™ software program (C-motion, Inc., Germantown, MD) was used to process the data files to produce histories of kinematic variables describing the volunteer's posture and gait. The kinematic data were analyzed to determine the extent to which gait parameters and body posture were affected by the armor conditions.

Oxygen consumption. $\dot{V}O_2$ was measured during treadmill walking and running using the $K4b^2$ metabolic analysis apparatus (COSMED, Rome, Italy). The apparatus includes a portable unit that contains the O_2 and CO_2 analyzers, sampling pump, UHF transmitter, barometric sensors, and electronics. The rate of oxygen consumption, as recorded with the $K4b^2$ unit, was expressed in absolute terms (ml/min). For analysis purposes, it was scaled to the volunteer's body mass (ml/kg/min) and to body mass plus the mass of all items worn on the body (ml/kg/min).

Testing

For walking trials, the force plate treadmill was set at a speed of 1.34 $m \cdot s^{-1}$ and a 0% grade. For running, treadmill speed was 2.24 $m \cdot s^{-1}$ and the grade was again 0%. Prior to the days of formal testing, volunteers were familiarized with walking and running on the force plate treadmill at these speeds. For familiarization, a volunteer first walked at 1.34 $m \cdot s^{-1}$ without any body armor. Then, the speed was gradually increased, and the volunteer ran at 2.24 $m \cdot s^{-1}$. Familiarization continued with the volunteer walking and then running at these same speeds for 10-min periods wearing the IBA alone and with each type of extremity armor.

On any one day of testing, a volunteer had four 10-min trials of walking or four 10-min trials of running. The volunteer walked or ran continuously throughout the 10-min period. A different armor condition was tested during each of the four trials. There was a 15-min rest period between trials. Within a running or a walking trial, force plate and camera outputs were recorded for 2 min after the trial had been underway for 5 min. Ten strides, five initiated with a right heel-strike and five with a left heel-strike, were selected for subsequent analysis from the recorded GRF data and motion data. At about 7 min into the trial, $\dot{V}O_2$ was measured for 90 s.

Repetitive Box Lift and Carry

Equipment and Measurements

This activity entails lifting a metal box by its handles and carrying it. The box is approximately 38 cm wide, 11 cm deep, and 23 cm high. There are opposing handles on two sides of the box. For this study, the box was weighted to 20.5 kg. The box is at the end of a smooth ramp, at floor level, 3.05 m away from and directly in front of a wooden platform. The height of the platform from the floor is 1.32 m (simulating the height of the bed of an Army 5-ton truck). The path from the box to the platform is a straight path without obstructions. The activity requires that an individual lift the box from the floor, walk to the platform, place the box on the platform, and return to the starting position for another box. The score on the activity is the number of cycles executed in a specified time period.

Testing

A trial of this activity consisted of lifting and then carrying a box to the platform as many times as possible within a 5-min period. The number of boxes carried to the platform each minute and the total number carried over 5 min were recorded. Volunteers were encouraged to complete as many cycles of this task as they could within the allotted time. The test was performed once under each armor condition. A volunteer did not participate in more than two trials on any single day, and there was a rest break of approximately 20 min between the two trials. Prior to the first day of testing, volunteers were given practice of this activity in order to learn how to execute it safely and to become familiar with performing the activity continuously for 5 min.

Grenade Throws

Equipment and Measurements

Training hand grenades were used for this activity. They were appropriately weighted to simulate a live grenade. A target, 1 m in diameter, was placed on the ground. A line was delineated on the ground, 30 m from the centroid of the target. The activity required that an individual throw a grenade at the target without crossing the line. Volunteers began in a squatting position, with both feet behind and parallel to the line and the nonthrowing shoulder pointed toward the target. They stood, took one step forward (with the foot on the side of the nonthrowing arm) and threw the grenade at the target. If more than one step was taken, or if the foot crossed over the line, the throw was not recorded, and another throw was completed. The distance from the throw line to the grenade point-of-initial-contact (distance thrown) and the distance from each grenade point-of-initial-contact to the center of the target (accuracy) were recorded.

Testing

One trial of this activity consisted of five throws. The distance and the accuracy of each throw were recorded, and a mean over the five throws was computed as the score for the trial. A

volunteer participated in one trial (five throws) under each armor condition and was tested in no more than three armor conditions on any one day. There was a rest break of approximately 10 min between trials. Immediately before a trial, the volunteer took three practice throws. In the days prior to testing, the volunteers also were familiarized with and practiced throwing until their throws became reasonably accurate.

30-m Rushes

Equipment and Measurements

Two padded gym mats were used. They were placed on the floor approximately 30 m apart. This activity started with a volunteer in a prone position on one mat facing the opposing mat. Upon an auditory signal from an investigator, the volunteer got up and ran forward, assumed a prone position on the opposing mat 30 m away, and faced the direction of the starting position. Five seconds later there was another auditory signal, upon which the volunteer proceeded in the same manner back to the starting position. This cycle was repeated until five 30-m rushes were completed. For scoring, the time to complete each individual rush and the total time to complete the five rushes were recorded.

Testing

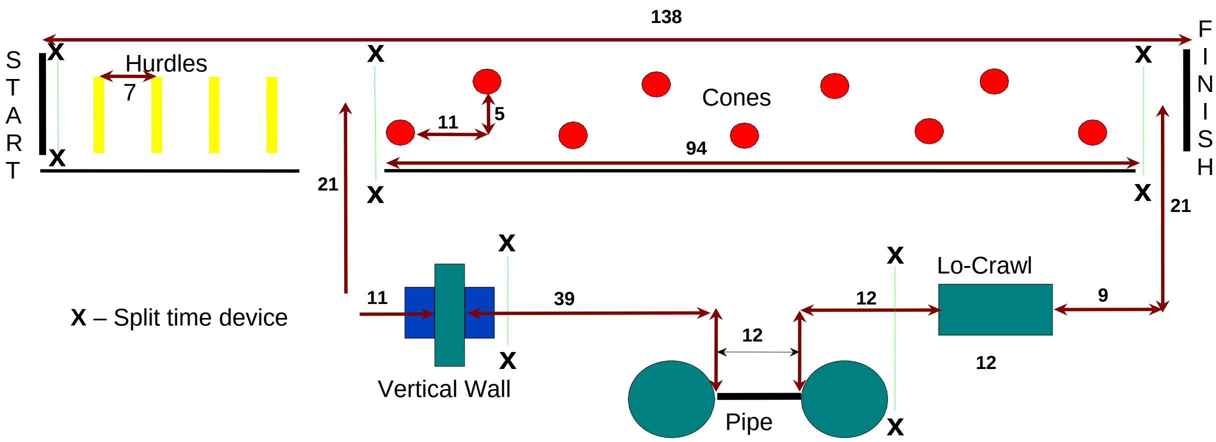
Volunteers participated in one trial (five rushes) under each armor condition. They were encouraged to complete each rush as quickly as possible. On any one day of testing, a volunteer participated in no more than two trials of this activity with a rest break of 10 min between the trials. Prior to the first trial of the day, volunteers warmed up by jogging for several minutes and performing several short, fast bursts of speed. On a day preceding testing, volunteers were familiarized with this activity by performing two to three rushes as quickly as possible.

Obstacle Course Runs

Equipment and Measurements

The obstacle course was located indoors at the Center for Military Biomechanics Research. The obstacle course was similar to the one depicted in Figure 5 and included:

- A set of four plastic hurdles, 0.6 m high
- A field of nine rubber cones delineating a zigzag running pattern, 27 m long and 1.5 m wide
- A crawl space of wood/wire, 0.6 m high, 0.9 m wide, and 3.7 m long
- A horizontal shimmy pipe, 3.7 m long
- A 1.4-m high sheer wooden wall without footholds or ropes
- A 27-m straight run



**Note.* First time through cone section zigzag run, second time straight run.
Numbers represent distance in ft.

Figure 5. Obstacle course layout.

Total course completion time and times to complete each obstacle or course segment were recorded using electronic timing devices (Brower Timing Devices, Salt Lake City, UT) placed along the course. The score was the total time to complete one run of the entire course.

Testing

One run of the obstacle course comprised a trial. Volunteers performed one trial under each armor condition. They were encouraged to complete the course as quickly as possible. A volunteer had no more than two runs of the course on a single day of testing and there was a 20-min rest break between trials. Before testing began, volunteers were familiarized with each obstacle and ran the course at about 75% of maximal effort.

Range of Motion Measurement and Human Factors Assessment

During this portion of the study, range of motion, ability to perform certain movements, ease of use, and comfort were assessed for the armor conditions. The activities comprising this portion of the study are described here.

Range of Motion

The volunteers executed a series of simple body mobility tasks. They were given three successive trials of each mobility task in each armor condition. The maximum extent of movement possible was measured by using either a meter stick or a gravity goniometer (Glanville & Kreezer, 1937; Leighton, 1942). A goniometer measures the angular displacement at a body joint (e.g., elbow, shoulder, knee). The score on a mobility task was the mean over the three trials under a given armor condition:

- Kneel and Rise: A volunteer was rated as to his ability to rise from a kneeling position, either with or without assistance. The volunteer began in a standing position, got down on both knees, and stood up again. The rating scale was: 0 = cannot get down on both knees;

1 = cannot rise from kneeling position without help from an investigator; 2 = can rise from kneeling position, but needs to grasp an object for support; 3 = can rise from kneeling position without any help at all.

- Walk Forward Five Steps: The volunteer took five steps forward, each as far forward as possible. The distance from the heel of the foot when starting to the toe of the foot upon taking the fifth step was measured with a meter stick and recorded.
- Standing Trunk Flexion: Volunteers were asked to attempt to touch the floor at a point just in front of their feet. The distance between the fingertips and the floor was measured with a meter stick.
- Upper Arm Abduction: Maintaining the body in an upright posture and starting with the arms at the sides, the volunteer raised both arms sideward and upward as far as possible. The movement from the starting position was measured with a goniometer.
- Shoulder Flexion With Elbow Extended: Maintaining the body in an upright posture and starting with the arms at the sides, the volunteer raised the right arm forward and up as far as possible, while keeping the elbow straight. The movement from the starting position was measured with a goniometer.
- Hip Flexion With Knee Extended: Holding the back of a chair for support, the volunteer raised the leg as far forward and up as possible, while keeping the knee straight. A goniometer was used to measure the amount of flexion.
- Upper Leg Flexion: Allowing the knee to bend freely, the volunteer raised the upper leg as far up as possible. The volunteer grasped a support (the back of a chair) while raising the leg. The amount of flexion was measured with a goniometer.

Movements

The volunteers executed a number of movements once under each armor condition. The movements, which are commonly performed by military personnel, were as follows:

- Prone firing position: The volunteer assumed a prone firing position, unsupported, and the ability to cheek and sight a mock M-4 carbine was documented.
- Kneeling firing position: The volunteer assumed a kneeling firing position, unsupported, and the ability to cheek and sight a mock M-4 carbine was documented.
- Squatting: The volunteer attempted to squat. The ability to do so and the ease with which it could be done were recorded.
- Climbing: The volunteer climbed a flight of stairs. The ability to complete the flight and the ease of doing so were recorded.

Other Human Factors Issues

Throughout the study, the investigators observed whether there were any problems that could cause injury to the Soldier or be detrimental to the mission. In addition, the investigators looked for other human factors issues throughout the study that were related to ease of use of the armor and compatibility with other military equipment. These included any difficulties the volunteers encountered when donning and adjusting the extremity armor and any displacement of the extremity armor components on the body when volunteers were carrying out physical activities.

Subjective Measures

Several techniques were used throughout the study to acquire information from the volunteers regarding the armor being tested. The Borg (1970) rating of perceived exertion (RPE) scale was administered to the volunteers in conjunction with their execution of a number of tests that comprised this study. The RPE scale, which is presented in Appendix A, provides the respondent with 15 categories for rating his perceived exertion, from *no exertion at all* (rest) to *maximal exertion*. The RPE was administered at the end of each 10-min bout of treadmill walking and of treadmill running, at the end of each 5-min trial of box lifting and carrying, and upon completion of each run of the obstacle course.

A questionnaire, which is referred to as the rating of pain, soreness, and discomfort (RPSD) questionnaire (Corlett & Bishop, 1976), was also administered to the volunteers at a number of points in the study. In this questionnaire, the respondent is to use a 5-point scale to rate the level of pain, soreness, discomfort or restriction being experienced at specific parts of the body (Appendix B). The RPSD was given immediately upon completion of each bout of running, each trial of box lifting and carrying, and each trial of grenade throwing.

Study-specific questionnaires were devised to obtain volunteers' opinions of the armor under test. These questionnaires were administered principally during the human factors assessment portion of the study.

3D Body Scanning

Equipment

A Cyberware WB4 whole-body 3D surface scanner (Cyberware, Inc., Monterey, CA) was used to capture body surface data for analysis of the body areas covered by ballistic-protective material. The WB4 utilizes low-powered planes of visible (red) and infrared laser light to illuminate a horizontal stripe around the body that is then digitized with standard digital cameras. Luminance or red-green-blue (RGB) color texture maps are captured during scanning, as well. The laser sources in the WB4 are rated Class II and produce low-intensity light with power similar to that of a barcode reader. The laser sources are compliant with US Department of Health and Human Services/Bureau of Radiological Health Radiation Performance Standards, 21 CFR, Chapter 1, Subchapter J, and are deemed safe for human use. The lasers in the Cyberware scanner take less than 1 s to pass across each eye during a scan and, therefore, pose a very low injury risk. Further eye safety is achieved by having the volunteer face toward the infrared lasers. In this position, the radiation is blocked by the water on the surface of the eye and thus does not penetrate into the eye itself. Additional safeguards include an automatic shut off for the lasers after 30 s and an emergency stop button on the motion system.

Testing

Each volunteer was scanned without armor and when outfitted in each of the armor conditions tested. To determine the body areas covered by ballistic-protective material, the scans of a volunteer without armor and in each of the armor conditions were first aligned. A distance

field matrix made up of the distance between points on the scan without armor to the closest point on the armored scan was then created. Next, body coverage was defined as any point on the scan without armor where the distance field matrix value was greater than a threshold of 5 mm. Finally, the surface area of coverage was computed from the collection of points on the scan without armor that were covered by ballistic-protective material (Figures 6 and 7).

Statistical Analyses

To address the objective of investigating the effects of body armor on performance, a one-way repeated measures analysis of variance (ANOVA), with four levels of the body armor variable (IBA, IDAS, DP/LEBA, QuadGuard), was carried out on each of the quantitative dependent measures recorded in this study and on the RPE ratings. All statistical analyses were accomplished using SPSS 13.0. An effect was statistically significant if the likelihood of its occurrence by chance was $p < .05$. In those instances in which an ANOVA yielded a significant main effect of body armor, post-hoc analyses in the form of the Least Significant Difference procedure were performed, with the significance level again set at $p < .05$.

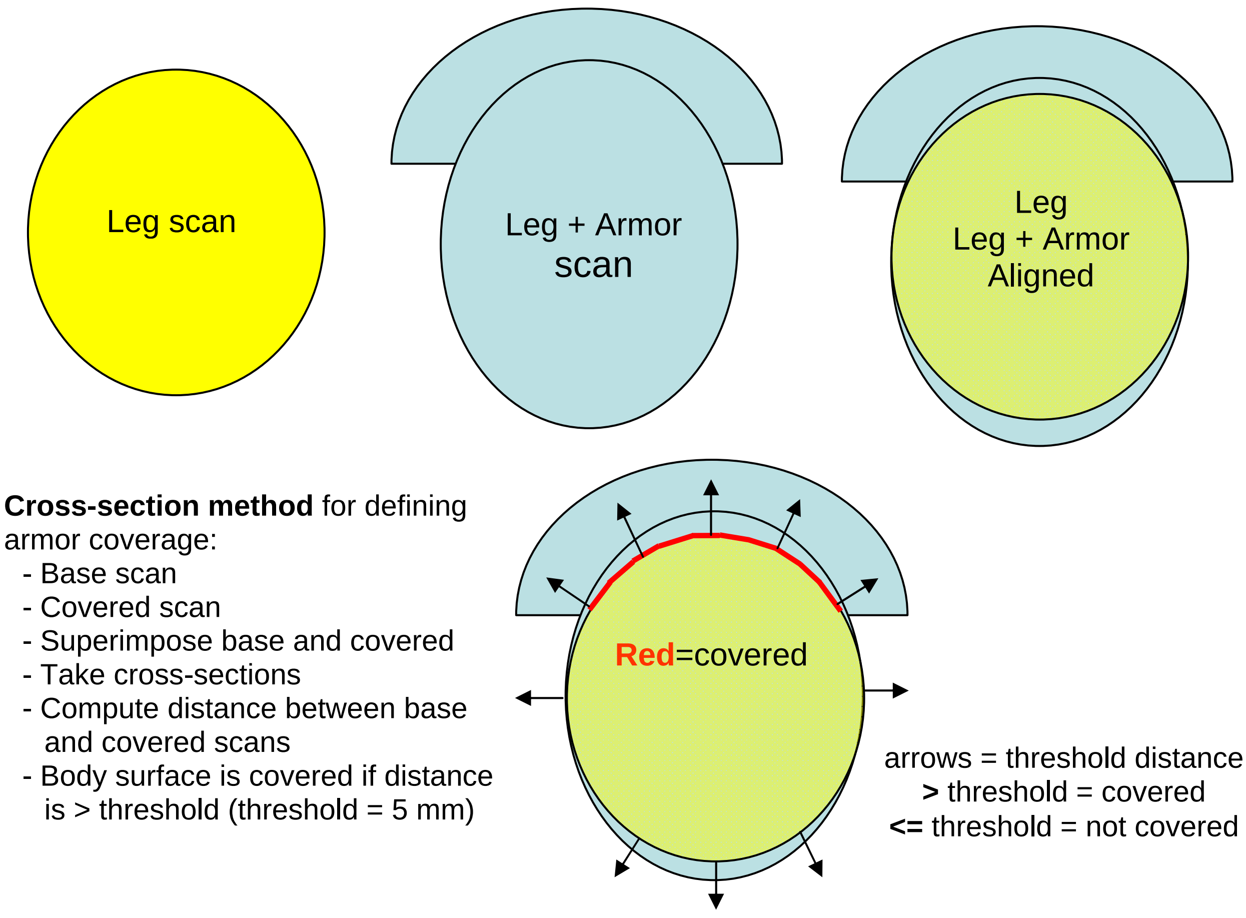


Figure 6. Cross-section method for defining armor coverage.

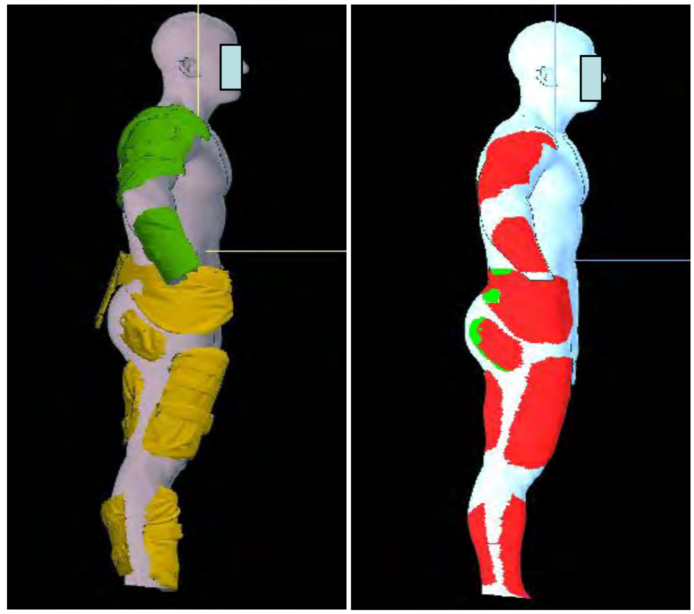


Figure 7. Example of 3D scan and coverage map for IDAS.

RESULTS

This chapter presents the results of the analyses carried out to assess the effects of the type of armor system worn on the dependent measures for energy usage and the biomechanics of walking and running. The data for measures taken to quantify performance on the box lift and carry, grenade throws, 30-m rushes, and obstacle course runs are also presented. The results are included as well for the range of motion measurements and other activities carried out as part of the human factors assessment of the armor systems, for the subjective measures used in the study, and for calculation of the body surface area covered by ballistic-protective material with each of the armor systems tested.

Most of the figures and tables in this chapter contain results of post-hoc statistical difference tests. Results of the tests are indicated by upper case letters. Armor conditions that do not share the same letter differed significantly in the post-hoc tests ($p < .05$). Conversely, those conditions that share the same letter were not significantly different ($p > .05$).

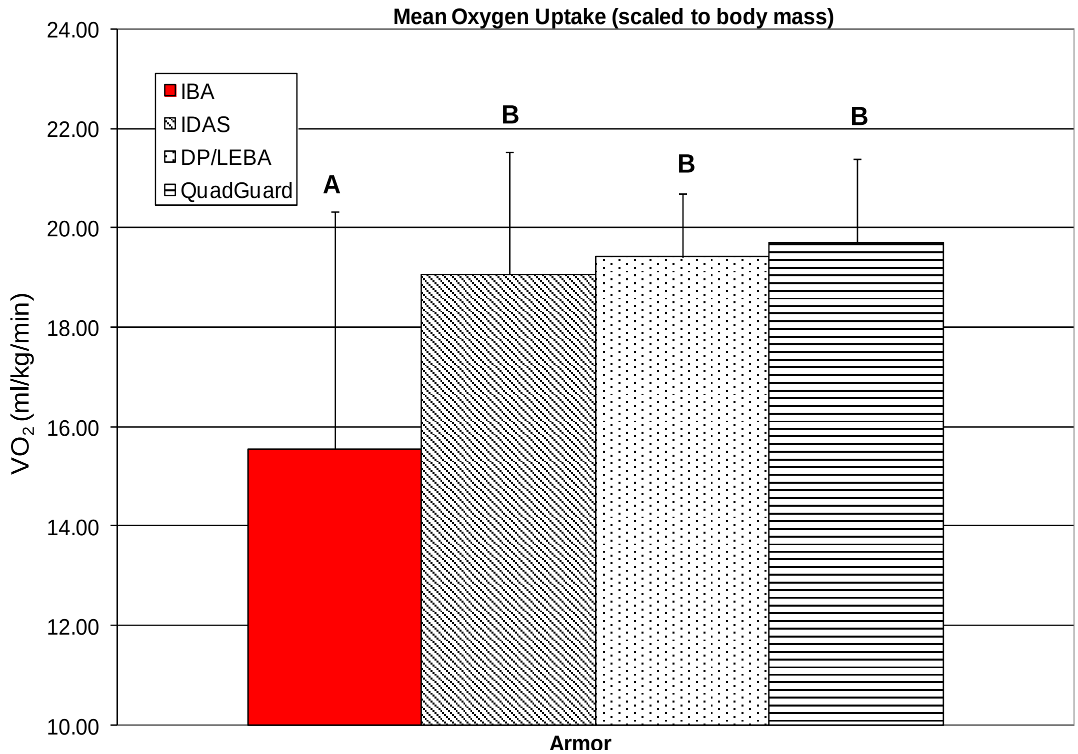
Energy Usage When Walking and Running

$\dot{V}O_2$ was the measure of the energy used wearing the armor systems while walking and running on a level treadmill at 1.34 and 2.24 $m \cdot s^{-1}$, respectively. The data were expressed as $\dot{V}O_2$ scaled to the volunteer's body mass, in ml/kg/min, and as $\dot{V}O_2$ scaled to total mass (body mass plus the mass of all clothing, equipment, and armor items worn), in ml/kg/min. The two forms of $\dot{V}O_2$ data were analyzed separately, and the results of the analyses are presented here in graphical form, along with means and standard deviations (*SD*) for the armor conditions.

Energy Usage When Walking

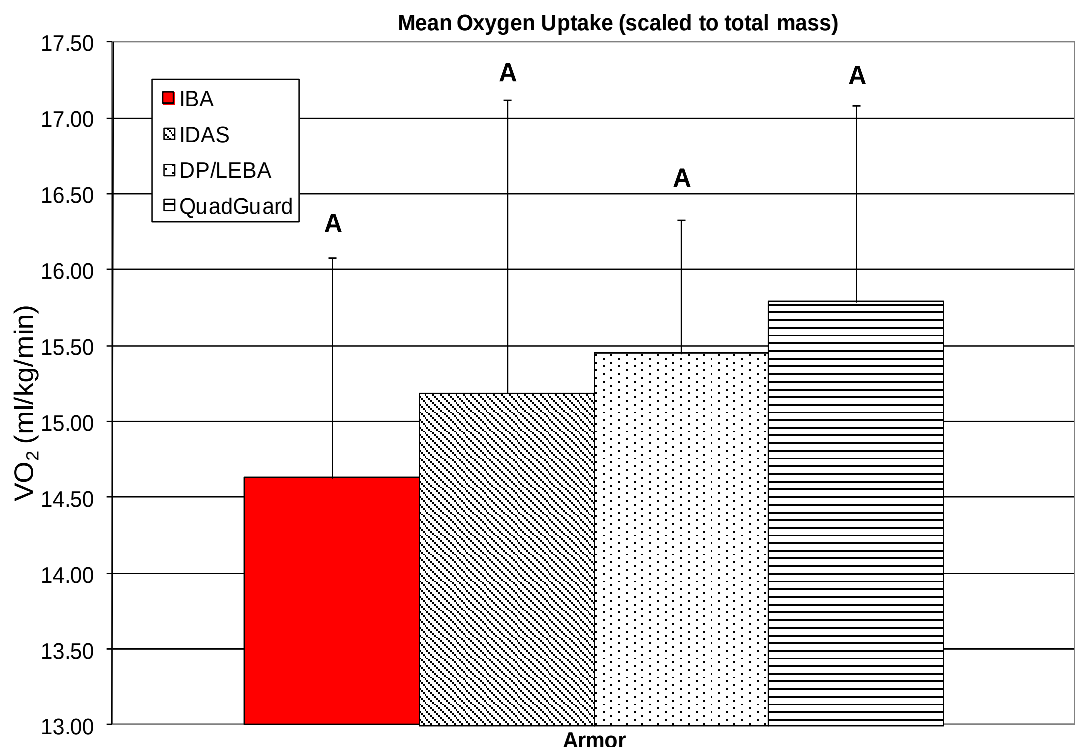
Comparisons of the body armor systems for energy use during walking, with $\dot{V}O_2$ scaled to body mass, revealed that the energy consumed was significantly lower with the IBA than with the extremity armor (Figure 8). Use of extremity armor increased oxygen consumption by 22 to 26% relative to the IBA. There were no significant differences among types of extremity armor when energy consumption was scaled to body mass.

Analysis of $\dot{V}O_2$ scaled to total mass did not yield a significant effect of body armor. However, the effect approached significance ($p < .06$). The most extreme difference in the means was between the IBA and the QuadGuard, with the energy consumed being lower for the IBA, but not significantly so (Figure 9).



Note. Armor conditions that do not share the same letter differed significantly in post-hoc tests ($p < .05$).

Figure 8. Mean (+1 *SD*) $\dot{V}O_2$ scaled to body mass for each armor condition during walking at 1.34 m·s^{-1} on a 0% grade ($N = 11$).

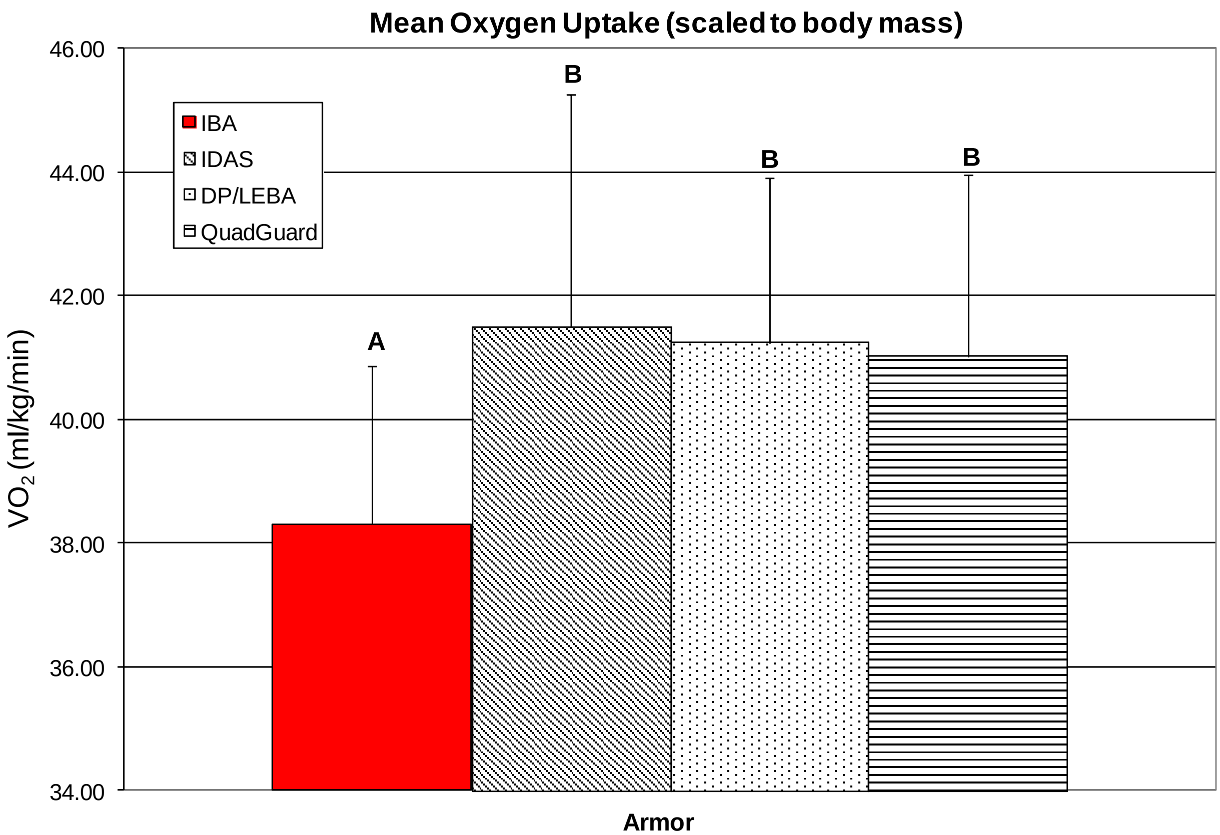


Note. Armor conditions that share same letter did not differ significantly in post-hoc tests ($p > .05$).

Figure 9. Mean (+1 *SD*) $\dot{V}O_2$ scaled to total mass for each armor condition during walking at 1.34 m·s^{-1} on a 0% grade ($N = 11$).

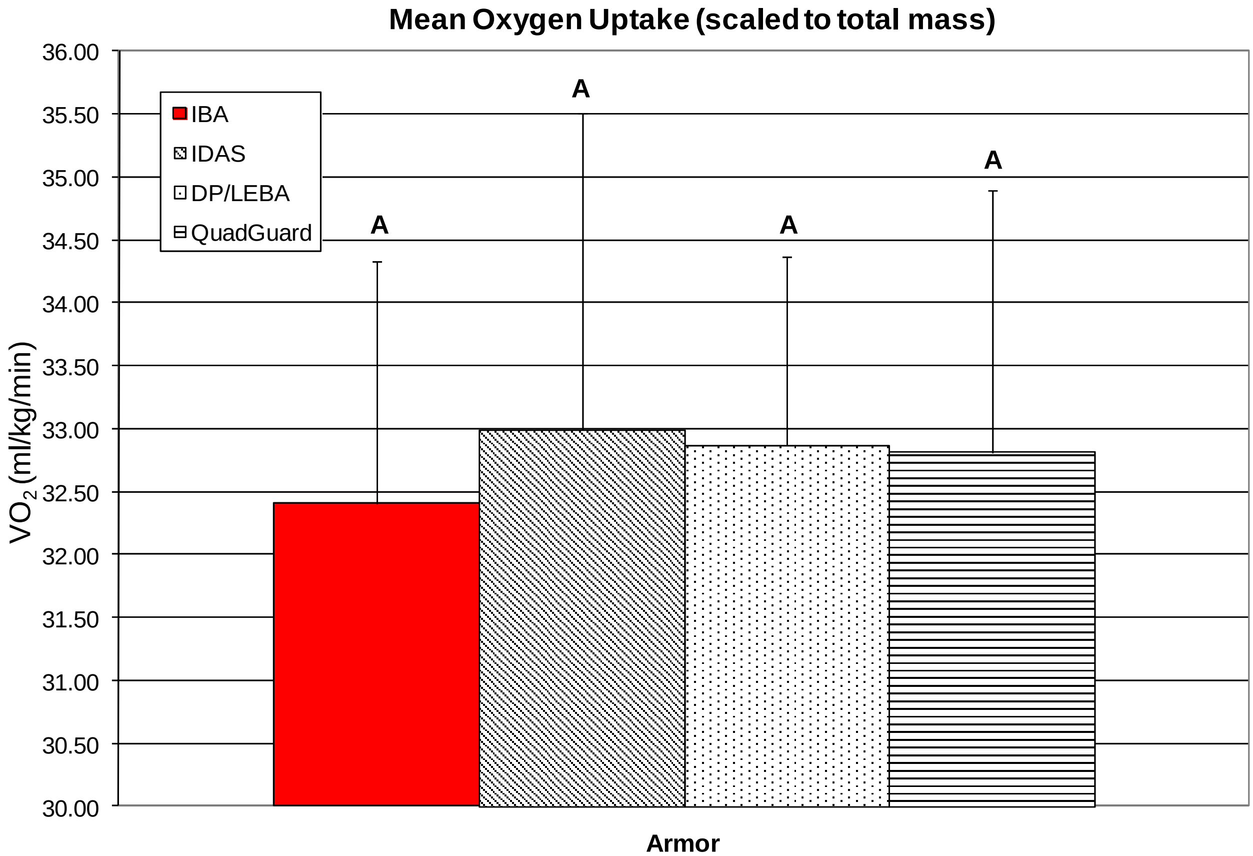
Energy Usage When Running

As was done in treating the walking data, the energy consumed wearing the armor configurations during running at 2.24 m·s^{-1} on a 0% grade was expressed as $\dot{V}O_2$ scaled to body mass and as $\dot{V}O_2$ scaled to total mass. When comparing the body armor system configurations using $\dot{V}O_2$ scaled to body mass, oxygen consumption was found to be significantly lower with the IBA than with the extremity armor (Figure 10). With the extremity armor, energy consumption was about 7% higher than it was with the IBA. There were no significant differences in $\dot{V}O_2$ among types of extremity armor. For $\dot{V}O_2$ scaled to total mass, the effect of armor condition was not significant and did not approach significance (p > .05; Figure 11).



Note. Armor conditions that do not share the same letter differed significantly in post-hoc tests (p < .05).

Figure 10. Mean (+1 *SD*) $\dot{V}O_2$ scaled to body mass for each armor condition during running at 2.24 m·s^{-1} on a 0% grade (N = 11).



Note. Armor conditions that share same letter did not differ significantly in post-hoc tests (p > .05).

Figure 11. Mean (+1 *SD*) $\dot{V}O_2$ scaled to total mass for each armor condition during running at 2.24 $m \cdot s^{-1}$ on a 0% grade (N = 11).

Biomechanics of Walking and Running

Variables calculated from the motion-time histories and the GRF-time histories recorded during walking at 1.34 $m \cdot s^{-1}$ and running at 2.24 $m \cdot s^{-1}$ on 0% grades were analyzed to examine the effects of the armor conditions on gait biomechanics. The findings are presented here.

Spatial and Temporal Gait Variables

Three gait variables were calculated from the motion-time histories. A spatial gait variable calculated was stride length. This was defined as the distance from the point of heel-strike of one foot with the ground to the point of the next heel-strike of the same foot with the ground. Similarly, cycle time, a temporal variable analyzed, was the time from heel-strike of one foot with the ground to the time of the next heel-strike of the same foot. Because treadmill speed was controlled throughout testing, at 1.34 or 2.24 $m \cdot s^{-1}$, volunteers had to adjust the lengths of their strides and the durations of their stride cycles to keep up with the movement of the treadmill. The stride length and the cycle time variables were of interest in this study because of the possibility that they would be differentially affected by the designs of the armor conditions being tested. If one of the armor configurations restricted volunteers' locomotor movements to a greater extent than another, it would be expected that stride lengths and cycle times would be shorter with this configuration. Thus, volunteers would be taking shorter strides and a higher

number of strides per unit time with the more restricting configuration. The need to maintain a higher stride frequency could, during prolonged walking or running, result in greater local muscle fatigue and, possibly, greater energy expenditure.

Another of the spatial gait variables analyzed was stride width. This was defined as the medial-lateral distance between the right and the left heels as measured at the time of heel-strike of each foot. This particular gait variable was calculated and analyzed in the present study in order to assess whether one or more of the extremity armor systems, possibly because of the thickness of the materials in the crotch or the thigh areas of the trousers, would result in the volunteers placing their feet wider apart during locomotion than other systems being tested. The wider foot placement could change other aspects of dynamic posture during locomotion, such as the extent of pelvic rotation or hip excursions.

Walking Gait

The three gait variables analyzed for the walking data were significantly affected by armor type. The means, the *SD*, and the post-hoc test results (i.e., the lettered subscripts) for each variable are presented in Table 3. As can be seen in the table, stride length and cycle time were shortest with the QuadGuard and longest with the IBA. The differences between these two conditions on the stride length and the cycle time variables were significant. Compared with the IBA, there was a reduction in stride length of about 2.5% and a reduction in cycle time of about 2.7% with the QuadGuard. The IDAS and the DP/LEBA did not differ significantly from each other or from the QuadGuard and the IBA on the stride length and the cycle time variables.

With regard to stride width during walking, the IBA had the lowest value. This value differed significantly from the values for the DP/LEBA and the QuadGuard (Table 3). With either of these types of extremity armor, stride width was about 12% greater than it was with the IBA. Stride width for the IDAS was about 6% greater than for the IBA. However, IDAS values did not differ significantly from those for the IBA, and the three types of extremity armor did not differ significantly from each other.

Table 3. *Means (SD) of Spatial and Temporal Gait Variables for Each Armor Condition During Walking at 1.34 m·s^{-1} on a 0% Grade (N = 11)*

	Armor			
Variable	IBA	IDAS	DP/LEBA	QuadGuard
Stride Length (m)	$1.533_{\mathbf{A}}$ (0.052)	$1.513_{\mathbf{AB}}$ (0.061)	$1.524_{\mathbf{AB}}$ (0.057)	$1.493_{\mathbf{B}}$ (0.071)
Cycle Time (s)	$1.104_{\mathbf{A}}$ (0.037)	$1.090_{\mathbf{AB}}$ (0.041)	$1.096_{\mathbf{AB}}$ (0.041)	$1.074_{\mathbf{B}}$ (0.049)
Stride Width (m)	$0.145_{\mathbf{A}}$ (0.017)	$0.154_{\mathbf{AB}}$ (0.027)	$0.164_{\mathbf{B}}$ (0.022)	$0.162_{\mathbf{B}}$ (0.024)

Note. For each dependent variable, means that do not share the same subscript differed significantly in post-hoc tests ($p < .05$).

Running Gait

The gait data for running are presented in Table 4. In the analyses of these data, stride width was the only one of the three variables analyzed that was significantly affected by armor type. As was the case with stride width for walking, the value for the IBA was lower than the values for the different types of extremity armor. The two highest values, those for the IDAS and the QuadGuard, were significantly greater than the value for the IBA. With either of these types of extremity armor, stride width was about 22% greater than it was with the IBA. The stride width values for the IDAS and the QuadGuard did not differ significantly from the value for the DP/LEBA.

Table 4. *Means (SD) of Spatial and Temporal Gait Variables for Each Armor Condition During Running at 2.24 m·s^{-1} on a 0% Grade (N = 11)*

	Armor			
Variable	IBA	IDAS	DP/LEBA	QuadGuard
Stride Length (m)	1.743_{A} (0.076)	1.750_{A} (0.076)	1.735_{A} (0.071)	1.739_{A} (0.071)
Cycle Time (s)	0.747_{A} (0.032)	0.747_{A} (0.030)	0.743_{A} (0.029)	0.741_{A} (0.028)
Stride Width (m)	0.093_{A} (0.014)	0.114_{B} (0.014)	0.109_{AB} (0.015)	0.114_{B} (0.024)

Note. For each dependent variable, means that do not share the same subscript differed significantly in post-hoc tests ($p < .05$).

GRF

A number of GRF variables were selected for analysis from the force-time histories of walking at 1.34 m·s^{-1} and running at 2.24 m·s^{-1}. In analyzing locomotion, GRF is generally decomposed into three orthogonal components. The directions of the components, which are at right angles to each other, are vertical, anterior-posterior, and medial-lateral. The vertical force is positive, which means that the positive direction is upward, indicating that the force is exerted by the ground on the foot. The anterior-posterior component, which is commonly referred to as the braking-propulsive component, is horizontal force exerted by the ground on the foot in the direction opposite locomotion (braking) or in the same direction as locomotion (propulsive). By convention, braking force is expressed as a negative number and propulsive force as a positive number. The medial-lateral component is horizontal force exerted by the ground on the foot toward or away from the midline of the body. The variables presented here were calculated from the vertical and the braking-propulsive components of the GRF. The GRF data were expressed as the measured force (N) normalized to the volunteer's body mass, in N·kg^{-1}, and as the force normalized to total mass (body mass plus the mass of all clothing, equipment, and armor items worn), in N·kg^{-1}. The two forms of the GRF data were analyzed separately, and the results of the analyses are presented here.

The patterns of force-time histories of walking strides differ somewhat among individuals. However, a typical configuration of the vertical GRF component shows two peaks. One occurs early in the stride cycle, at initial contact of the foot with the ground (i.e., heel-

strike), and the other occurs later in the stride cycle when the foot is pushing off from the ground (i.e., toe-off). The anterior-posterior component also tends to have two peaks: a braking peak during the initial phase of ground contact and a propulsive peak during the later phase. The walking data in this study were analyzed for peak vertical forces at heel-strike and at toe-off and for peak braking and propulsive forces.

As with walking, the patterns of force-time histories of running strides differ somewhat among individuals. A characteristic configuration of the vertical GRF component during running, however, shows a peak associated with heel-strike and a second associated with toe-off. The first peak in the vertical force component of a running stride, often referred to as the impact peak, is characterized by a rapid onset and a relatively large force. The anterior-posterior GRF component also tends to have two peaks: a braking peak during the initial phase of ground contact and a propulsive peak during the later phase. The GRF variables analyzed here for running were peak vertical forces at heel-strike and at toe-off and peak braking and propulsive forces.

GRF is a distributed force that acts over the entire surface of the foot or the shoe that is in contact with the ground. Although GRF does not reveal the magnitude of the forces within the skeleton during ground contact, examination of the components of the GRF does give some insight into the forces that the total body is exposed to every time the foot contacts and subsequently pushes off from the ground during walking and running. In this study, the GRF variables selected for analysis were those that capture the highest magnitude forces during ground contact and, therefore, those of greatest interest in assessing differences in the armor conditions tested.

GRF During Walking

The means, the *SD*, and the results of the post-hoc tests (i.e., the lettered subscripts) for the peak vertical GRFs at heel-strike and at toe-off are presented in Table 5. The analysis of the heel-strike data expressed as peak vertical force normalized to body mass yielded peak forces that were significantly higher with the extremity armor than with the IBA. Further, the heel-strike forces with the IDAS and the DP/LEBA were significantly higher than the forces with the QuadGuard. Analysis of peak heel-strike vertical force normalized to total mass revealed that the lowest forces occurred when the QuadGuard was used; the forces for the IBA and the IDAS were significantly higher than those for the QuadGuard.

The data for peak vertical force at toe-off normalized to body mass yielded peak forces for the IBA that were significantly lower than those for the extremity armor, but there were no significant differences among the three types of extremity armor (Table 5). When normalized to total mass, there were no significant differences among body armor conditions on the peak vertical force at toe-off.

Table 5. *Means (SD) of Vertical GRF at Heel-Strike and at Toe-Off for Each Armor Condition During Walking at 1.34 m·s^{-1} on a 0% Grade (N = 11)*

	Armor			
Variable	IBA	IDAS	DP/LEBA	QuadGuard
	Force Normalized to Body Mass (N·kg^{-1})			
Heel-Strike	$12.54_{\mathbf{A}}$ (0.55)	$13.35_{\mathbf{C}}$ (0.78)	$13.36_{\mathbf{C}}$ (0.68)	$13.09_{\mathbf{B}}$ (0.63)
Toe-Off	$12.59_{\mathbf{A}}$ (0.67)	$13.48_{\mathbf{B}}$ (0.87)	$13.51_{\mathbf{B}}$ (1.00)	$13.46_{\mathbf{B}}$ (0.82)
	Force Normalized to Total Mass (N·kg^{-1})			
Heel-Strike	$10.76_{\mathbf{B}}$ (0.46)	$10.67_{\mathbf{B}}$ (0.51)	$10.64_{\mathbf{AB}}$ (0.40)	$10.49_{\mathbf{A}}$ (0.44)
Toe-Off	$10.81_{\mathbf{A}}$ (0.47)	$10.77_{\mathbf{A}}$ (0.60)	$10.76_{\mathbf{A}}$ (0.67)	$10.79_{\mathbf{A}}$ (0.52)

Note. For each dependent variable, means that do not share the same subscript differed significantly in post-hoc tests ($p < .05$).

The means, the *SD*, and the results of the post-hoc tests (i.e., the lettered subscripts) for the peak braking and propulsive GRFs during walking are presented in Table 6. For the heel-strike data expressed as peak braking force normalized to body mass, the IBA had the lowest magnitude forces. However, the values for the IBA did not differ significantly from those for the IDAS or the QuadGuard. The highest magnitude forces were found for the DP/LEBA, and these forces were significantly higher than those for the IBA and the QuadGuard. When peak braking force was normalized to total mass, there were no significant differences among armor conditions.

Table 6. *Means (SD) of Braking and Propulsive GRF for Each Armor Condition During Walking at 1.34 m·s^{-1} on a 0% Grade (N = 11)*

	Armor			
Variable	IBA	IDAS	DP/LEBA	QuadGuard
	Force Normalized to Body Mass (N·kg^{-1})			
Braking	$-2.15_{\mathbf{A}}$ (0.28)	$-2.30_{\mathbf{AB}}$ (0.37)	$-2.40_{\mathbf{B}}$ (0.40)	$-2.25_{\mathbf{A}}$ (0.35)
Propulsive	$2.21_{\mathbf{A}}$ (0.15)	$2.41_{\mathbf{B}}$ (0.21)	$2.45_{\mathbf{B}}$ (0.19)	$2.39_{\mathbf{B}}$ (0.16)
	Force Normalized to Total Mass (N·kg^{-1})			
Braking	$-1.84_{\mathbf{A}}$ (0.23)	$-1.83_{\mathbf{A}}$ (0.27)	$-1.91_{\mathbf{A}}$ (0.29)	$-1.80_{\mathbf{A}}$ (0.26)
Propulsive	$1.90_{\mathbf{A}}$ (0.14)	$1.93_{\mathbf{A}}$ (0.18)	$1.95_{\mathbf{A}}$ (0.16)	$1.92_{\mathbf{A}}$ (0.14)

Note. For each dependent variable, means that do not share the same subscript differed significantly in post-hoc tests ($p < .05$).

With regard to the toe-off data, the IBA had peak propulsive forces normalized to body mass that were significantly lower than those for the extremity armor conditions, but there were no significant differences among the types of extremity armor (Table 6). When normalized to total mass, there were no differences among any of the armor conditions.

GRF During Running

Table 7 contains the summary statistics and the results of the post-hoc tests for the peak vertical GRFs at heel-strike during running. When normalized to body mass, the forces for the IBA were lowest in magnitude. They differed significantly from the forces for the IDAS and the QuadGuard, which did not differ from each other. The force values for the DP/LEBA did not differ from the values for any other armor conditions. When peak GRFs at heel-strike during running were normalized to total mass, there were no significant differences among armor conditions.

Table 7. *Means (SD) of Vertical GRF at Heel-Strike for Each Armor Condition During Running at 2.24 m·s^{-1} on a 0% Grade (N = 11)*

	Armor			
Variable	IBA	IDAS	DP/LEBA	QuadGuard
Force Normalized to Body Mass (N·kg^{-1})	$23.36_{\mathbf{A}}$ (2.28)	$24.79_{\mathbf{B}}$ (2.54)	$23.96_{\mathbf{AB}}$ (2.48)	$24.72_{\mathbf{B}}$ (2.63)
Force Normalized to Total Mass (N·kg^{-1})	$20.03_{\mathbf{A}}$ (1.72)	$19.79_{\mathbf{A}}$ (1.69)	$19.07_{\mathbf{A}}$ (1.66)	$19.80_{\mathbf{A}}$ (1.85)

Note. For each dependent variable, means that do not share the same subscript differed significantly in post-hoc tests (p < .05).

The data for peak braking and peak propulsive forces during running are presented in Table 8. For peak braking force at heel-strike normalized to body mass, the forces for the IBA and the QuadGuard were significantly lower than those for the IDAS and the DP/LEBA. There were no other significant differences among armor conditions on this measure. When peak braking force was normalized to total mass, the forces for the QuadGuard were significantly lower than those for the IDAS and the DP/LEBA.

The propulsive forces at toe-off during running were significantly affected by armor condition when normalized to body mass. As can be seen in Table 8, the significant difference was between the lowest magnitude forces, those for the IBA, and the highest magnitude forces, those for the IDAS. When normalized to total mass, no significant differences were obtained among armor conditions on the peak propulsive force measure.

Table 8. *Means (SD) of Braking and Propulsive GRF for Each Armor Condition During Running at 2.24 m·s^{-1} on a 0% Grade (N = 11)*

	Armor			
Variable	IBA	IDAS	DP/LEBA	QuadGuard
	Force Normalized to Body Mass (N·kg^{-1})			
Braking	$-2.44_{\mathbf{A}}$ (0.31)	$-2.74_{\mathbf{B}}$ (0.36)	$-2.65_{\mathbf{B}}$ (0.30)	$-2.51_{\mathbf{A}}$ (0.37)
Propulsive	$1.59_{\mathbf{A}}$ (0.32)	$1.79_{\mathbf{B}}$ (0.38)	$1.64_{\mathbf{A}}$ (0.36)	$1.69_{\mathbf{AB}}$ (0.31)
	Force Normalized to Total Mass (N·kg^{-1})			
Braking	$-2.10_{\mathbf{AB}}$ (0.26)	$-2.19_{\mathbf{B}}$ (0.28)	$-2.11_{\mathbf{B}}$ (0.21)	$-2.01_{\mathbf{A}}$ (0.27)
Propulsive	$1.36_{\mathbf{A}}$ (0.26)	$1.43_{\mathbf{A}}$ (0.28)	$1.30_{\mathbf{A}}$ (0.27)	$1.35_{\mathbf{A}}$ (0.24)

Note. For each dependent variable, means that do not share the same subscript differed significantly in post-hoc tests ($p < .05$).

Performance Tests

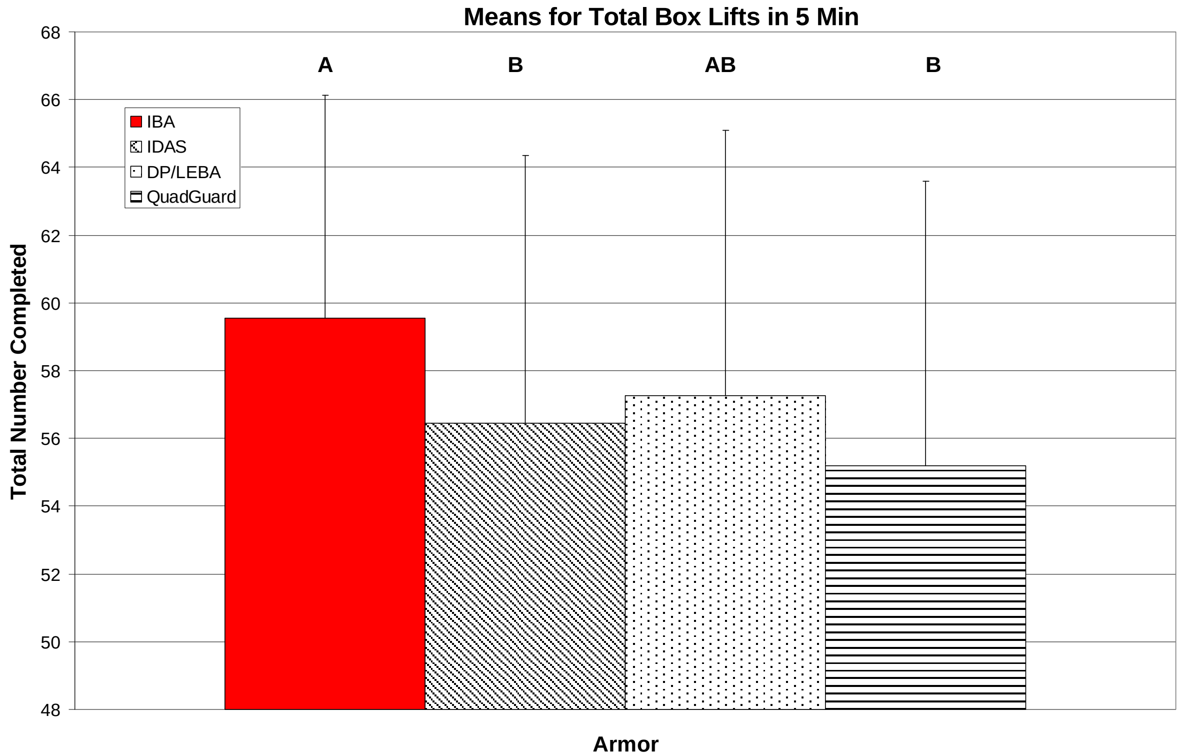
The performance tests of box lift and carry, grenade throws, 30-m rushes, and obstacle course runs were selected for inclusion in this study because these tests are related to activities that Soldiers and Marines perform in the field. Furthermore, body armor is likely to be worn while executing these types of activities. In addition, each of the tests could be administered in a standardized manner, and performance on each test could be readily quantified. The results for the performance tests are presented here.

Repetitive Box Lift and Carry

The cycles completed on the box lift and carry task in a 5-min period were analyzed to assess differences among the armor conditions. The means, the *SD*, and the results of the statistical analysis of the data (i.e., the letters above the means) are presented in Figure 12. The analysis revealed that significantly more cycles of the task were completed with the IBA than with the IDAS or the QuadGuard. The number of cycles completed with the DP/LEBA was intermediate and did not differ significantly from the number with the other armor configurations.

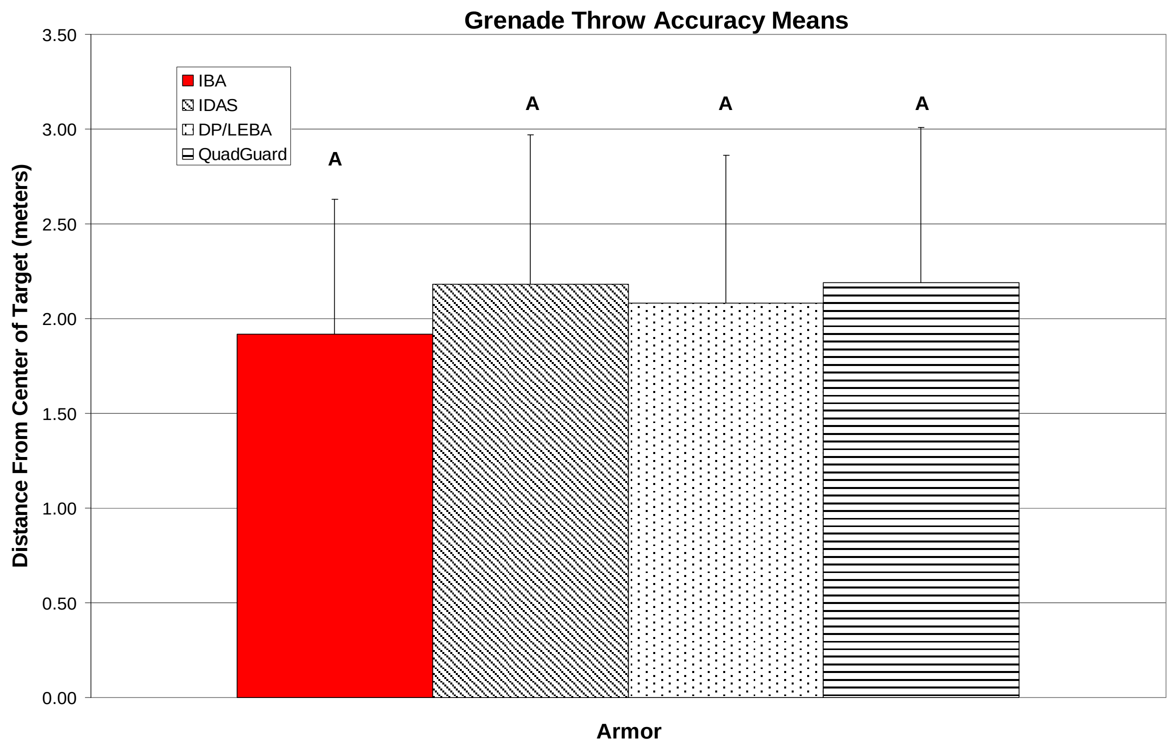
Grenade Throws

The distance thrown and the accuracy of the grenade throws were analyzed. The distance of the throw was measured from the throw line to the spot on the ground where the grenade landed. The accuracy was the distance from the center of the target, which was 30 m from the throw line, to the spot where the grenade landed. The accuracy data are presented in Figure 13. Armor condition did not have a significant effect on either the distance or the accuracy measures.



Note. Armor conditions that do not share the same letter differed significantly in post-hoc tests ($p < .05$).

Figure 12. Mean (+1 *SD*) number of box lift and carry cycles completed in 5 min for each armor condition ($N = 11$).

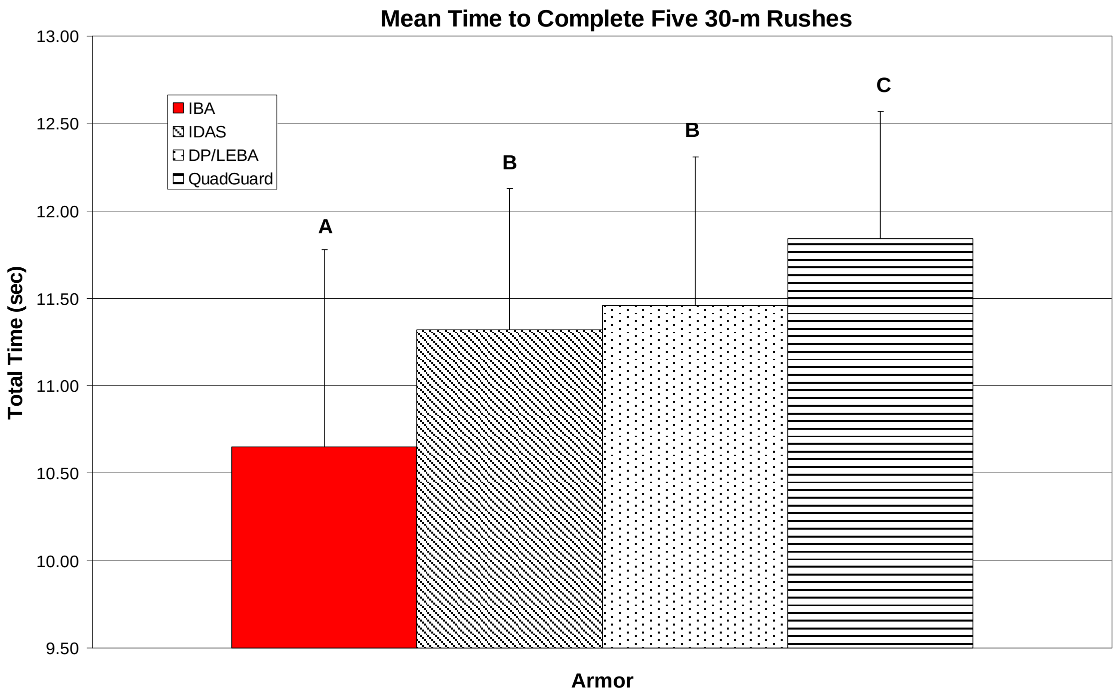


Note. Armor conditions that share same letter did not differ significantly in post-hoc tests ($p > .05$).

Figure 13. Mean (+1 *SD*) distance of the grenade throws from the center of the target for each armor condition ($N = 11$).

30-m Rushes

Two separate analyses were carried out on the data for the 30-m rushes to assess the effects of the armor configurations on this task. One analysis was done on the total time to complete all five rushes. The mean times, the *SD*, and the results of this analysis (i.e., the letters above the means) are presented in Figure 14. It was found that the total time to complete the activity was significantly slower for the extremity armor conditions than for the IBA. It was also found that the slowest time, which occurred with the QuadGuard, was significantly slower than the times for all other armor conditions.



Note. Armor conditions that do not share the same letter differed significantly in post-hoc tests ($p < .05$).

Figure 14. Mean (+1 *SD*) total time to complete five rushes for each armor condition ($N = 11$).

For the second analysis of the 30-m rush data, the times for each of the five successive rushes were analyzed, with the independent variables being armor condition and rush number. A plot of the data is presented in Figure 15. The analysis yielded a significant interaction between armor condition and rush number. It can be seen in Figure 15 that, regardless of armor condition, the times to complete successive rushes increased. However, the time increases were greater with the QuadGuard than with the other armor conditions. The difference between the first and the fifth rush mean times was 2.1 s for the QuadGuard, whereas the difference was 1.5 s for the DP/LEBA and 1 s for the IBA and the IDAS.

Obstacle Course Runs

The mean run times, the *SD*, and the results of the analysis of the obstacle course times (i.e., the letters above the means) are presented in Figure 16. It was found that the times for the IBA were significantly faster than those for the extremity armor. Further, there were no significant differences among the types of extremity armor.

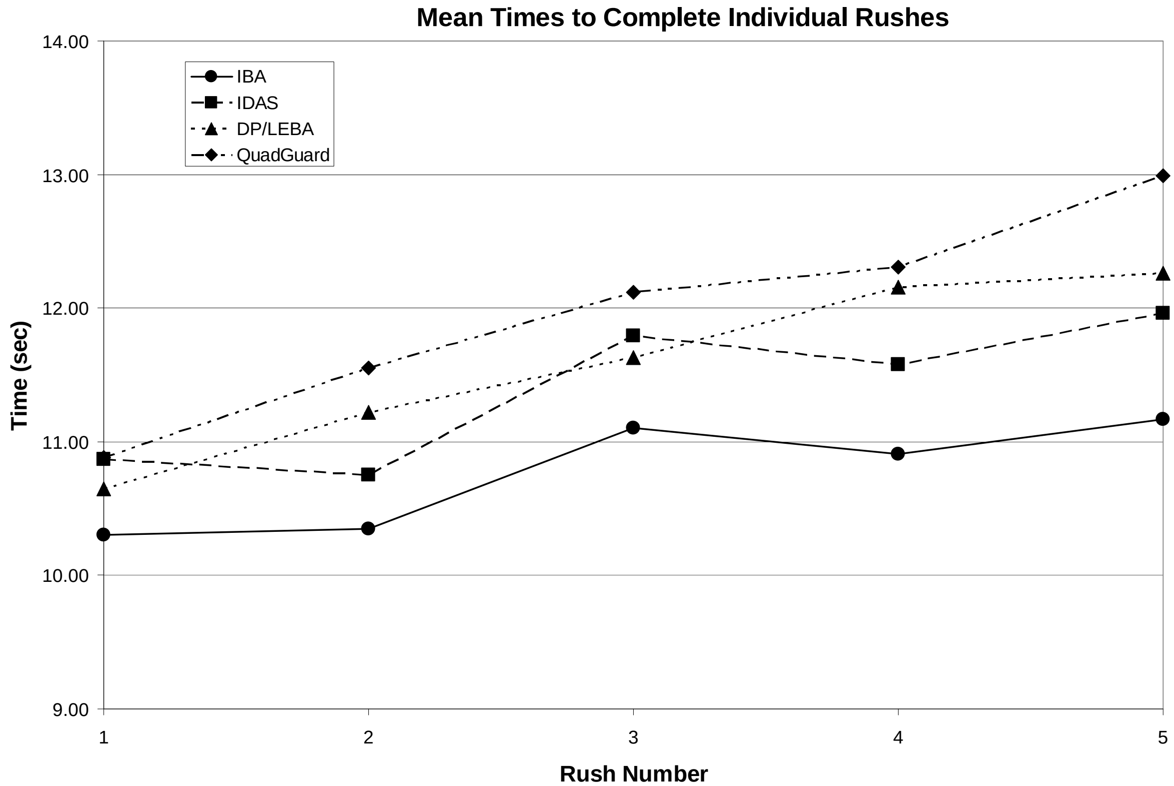
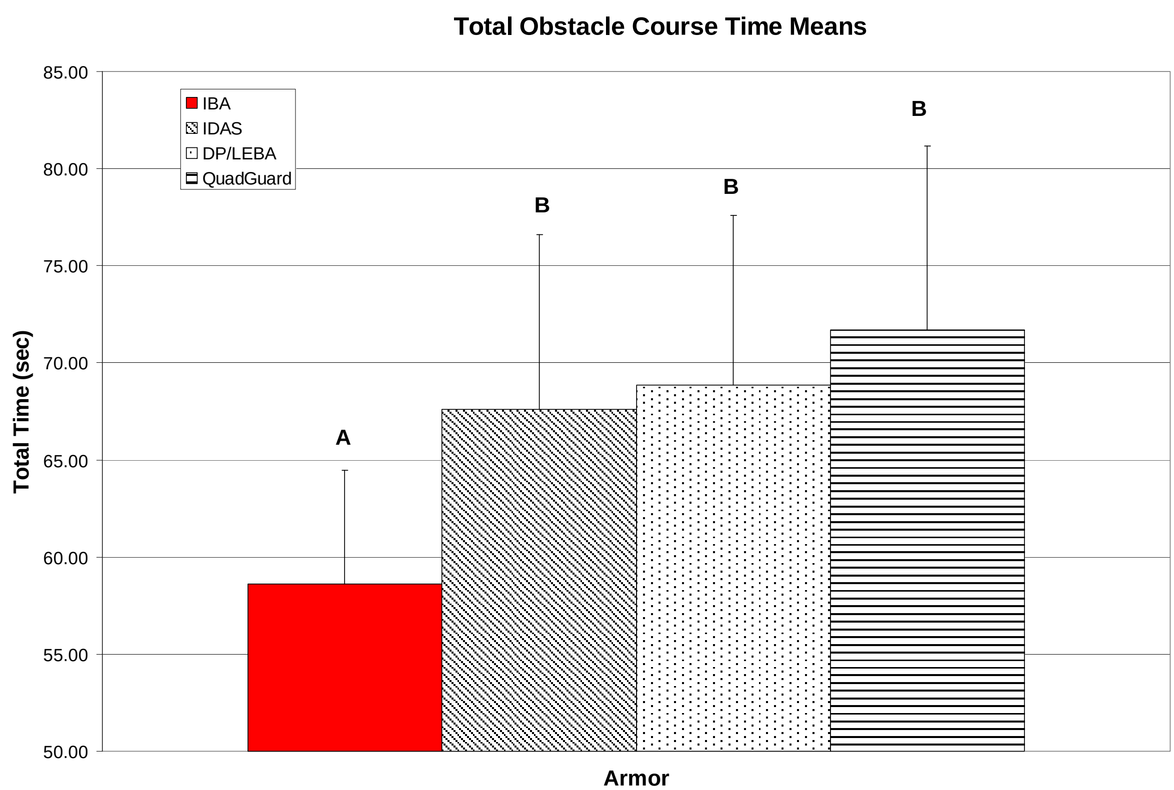


Figure 15. Mean times to complete each of five successive rushes for each armor condition (N = 11).



Note. Armor conditions that do not share the same letter differed significantly in post-hoc tests ($p < .05$).

Figure 16. Mean (+1 *SD*) time to complete the obstacle course for each armor condition (N = 11).

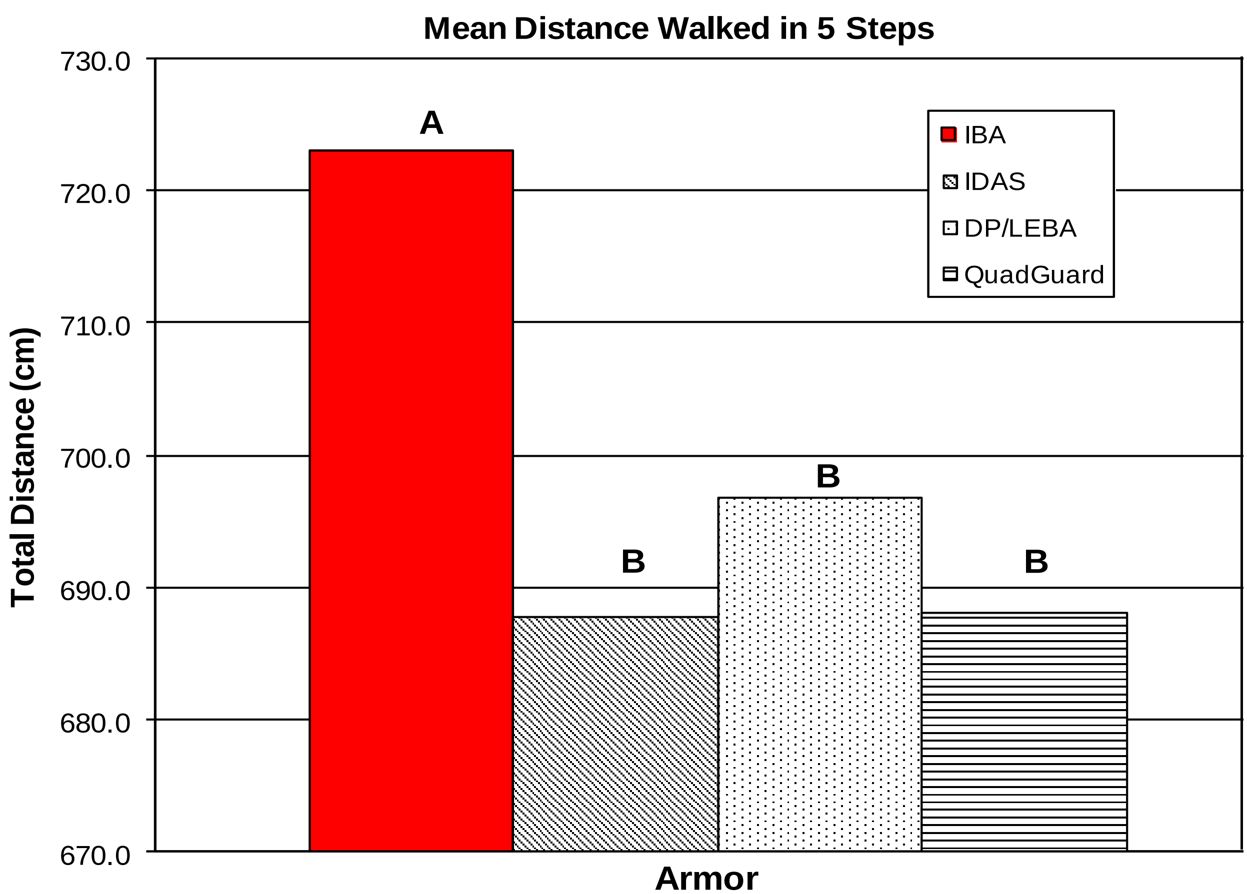
Range of Motion

The volunteers performed simple body movements in each of the four types of armor. Each movement required the maximum extent of motion, which could be quantified. Therefore, comparisons of the ranges of motion associated with each type of armor give some indication of the extent to which the armor may restrict body movement.

Kneel and Rise, Walk Forward for Distance, and Standing Trunk Flexion Motions

One movement required the volunteers to assume a kneeling position and then to rise to a standing position. Regardless of armor type, all volunteers executed this movement without assistance (a score of 3) for each armor condition.

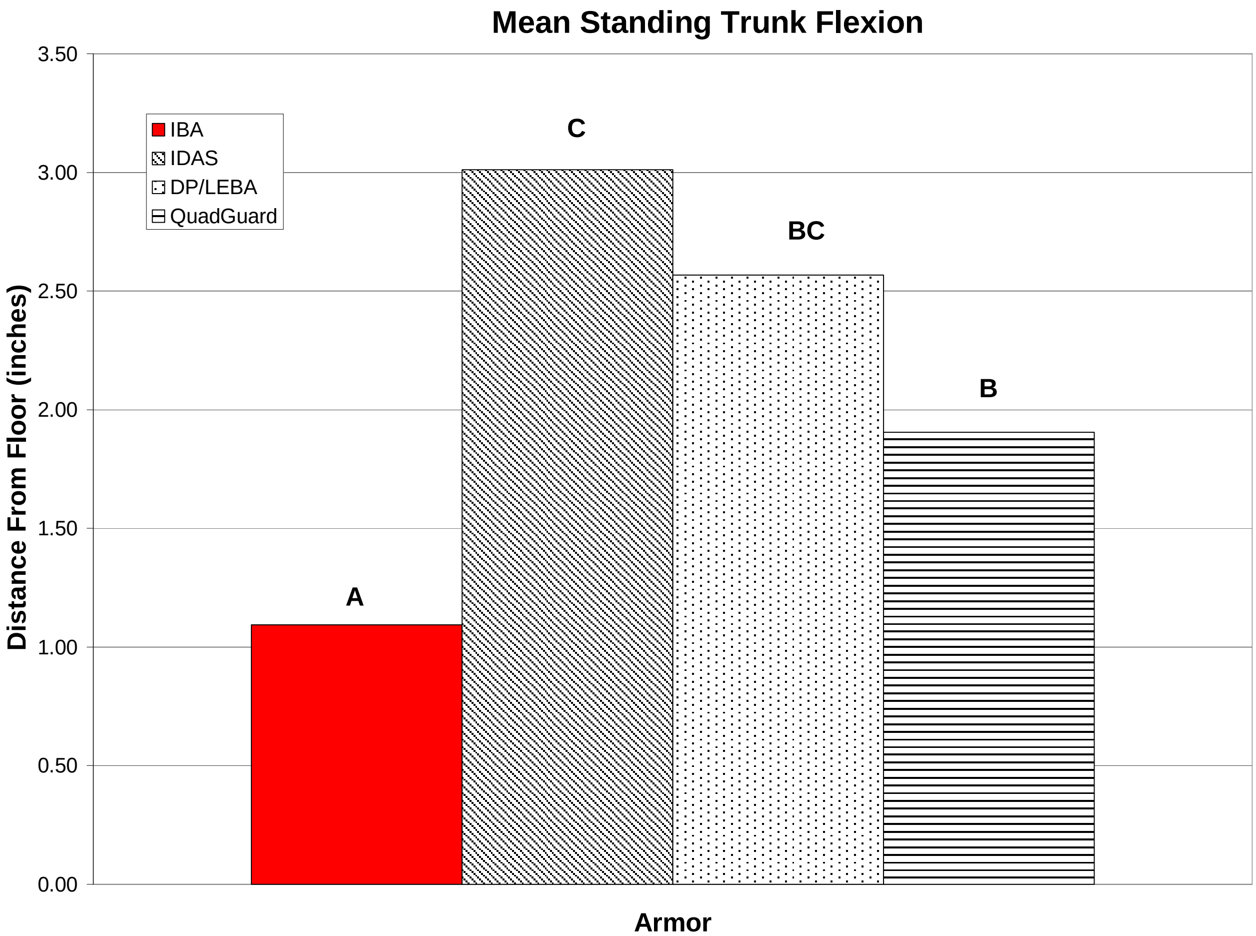
The second movement in this group entailed taking five steps forward. The means and the results of the analysis (i.e., the letters above the means) applied to this movement are presented in Figure 17. Each step taken was to be as long as possible. In the analysis of these data, it was found that the distances that could be traversed in five steps were significantly less with the extremity armor than with the IBA. There were no significant differences among the types of extremity armor.



Note. Armor conditions that do not share the same letter differed significantly in post-hoc tests ($p < .05$).

Figure 17. Mean distance walked in five steps forward for each armor condition ($N = 11$).

The third movement, standing trunk flexion, required that the volunteers, beginning in an upright standing position, reach their hands down to try to touch the floor without bending their knees. For this movement, lower scores indicate that the volunteers reached closer to the floor. The data for this movement are in Figure 18. Again, the extremity armor conditions yielded scores that were significantly inferior to those for the IBA. There were also differences among the types of extremity armor: the QuadGuard scores were significantly better than those for the IDAS.



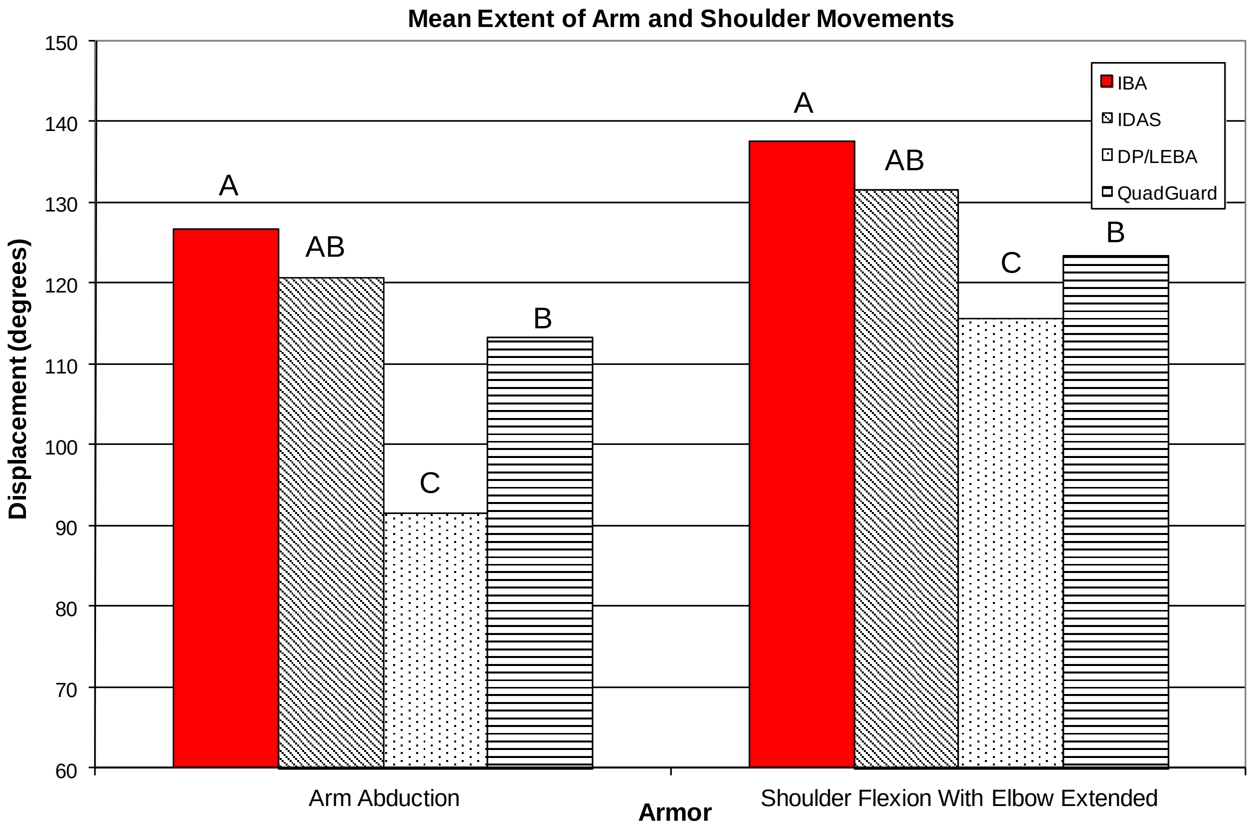
Note. Armor conditions that do not share the same letter differed significantly in post-hoc tests ($p < .05$).

Figure 18. Mean distance measured from floor for each armor condition on standing trunk flexion movement ($N = 11$).

Arm Abduction/Shoulder Flexion and Hip Flexion/Leg Flexion Motions

The volunteers performed two motions involving movement of the arm at the shoulder, arm abduction and shoulder flexion. For arm abduction, the arm was moved away from the side of the body and upward as far as possible while keeping the arm straight. Shoulder flexion entailed raising the arm forward and as far up as possible, keeping the elbow extended. The data for the maximum extent of both movements in each armor condition are presented in Figure 19. The results for the two movements were similar. There was a significantly greater range of movement with the IBA than with the DP/LEBA and the QuadGuard. The DP/LEBA had the

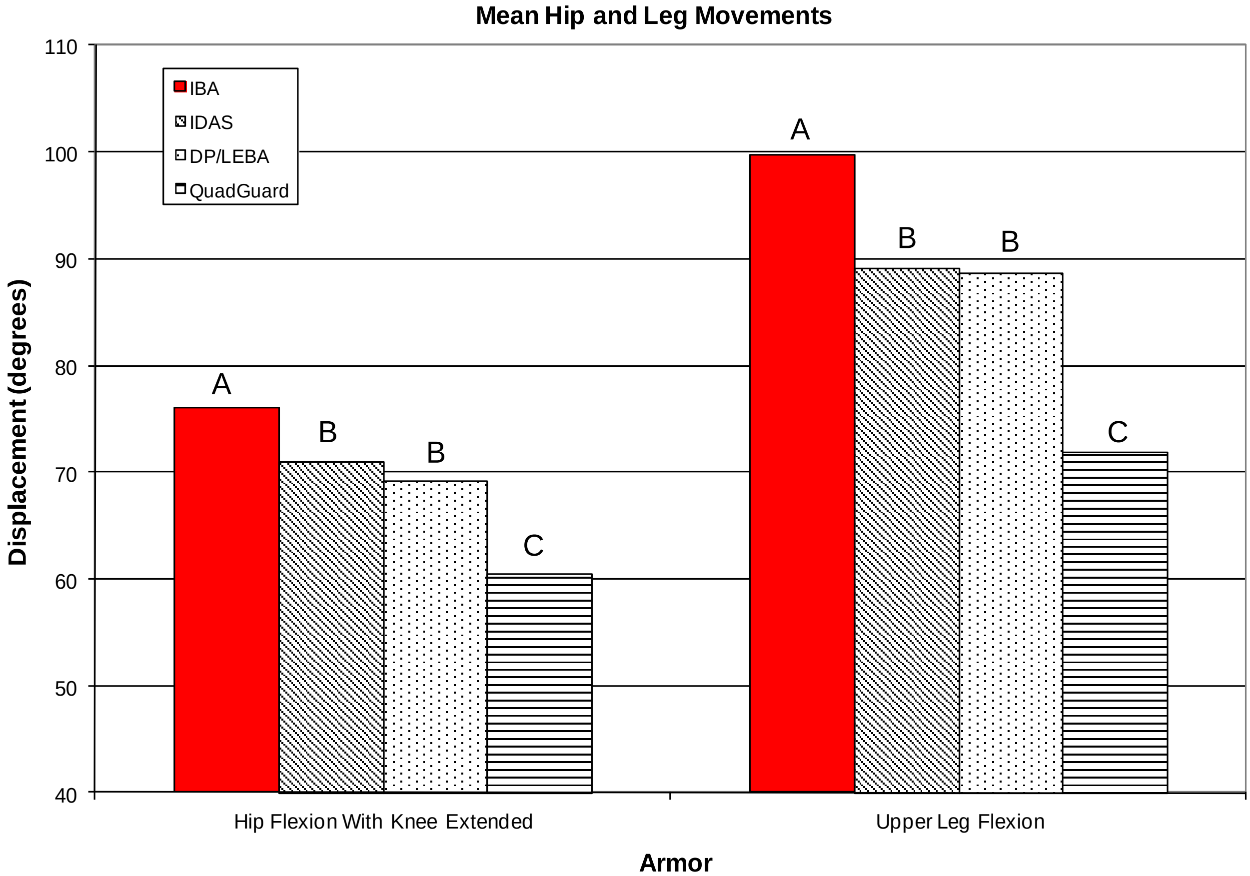
lowest range of movement; it was significantly lower than the range of movement for all of the other conditions.



Note. Armor conditions that do not share the same letter differed significantly in post-hoc tests ($p < .05$).

Figure 19. Mean extent of arm abduction and shoulder flexion with elbow extended for each armor condition ($N = 11$).

Two movements of the leg at the hip were also executed by the volunteers: hip flexion with the knee extended and upper leg flexion. In hip flexion, the right leg was moved forward as far as possible with the knee kept straight. Leg flexion required that the right upper leg be lifted up as far as possible while letting the lower leg swing freely from the knee. The analyses of these leg movements yielded similar results. For both movements, the extent of motion was significantly greater with the IBA than with the extremity armor (Figure 20). Among the extremity armor conditions, the extent of motion was significantly less with the QuadGuard than with the IDAS or the DP/LEBA.



Note. Armor conditions that do not share the same letter differed significantly in post-hoc tests ($p < .05$).

Figure 20. Mean extent of hip flexion with knee extended and leg flexion for each armor condition ($N = 11$).

Human Factors Assessment of the Body Armor for Mobility, Ease of Use, and Compatibility With Military Equipment and Activities

During the human factors portion of the study, the volunteers executed a number of movements using each armor condition. The investigators observed the ease with which the movements were carried out and sought feedback from the volunteers regarding any problems encountered. The volunteers also used military equipment with the armor, and the compatibility among the items was assessed. Further, throughout the study, the investigators noted any difficulties in use of the armor and any incompatibilities between the armor and execution of study activities. In addition, verbal feedback regarding the armor was elicited from the volunteers as they performed the various activities comprising the study. Summaries of the investigators' observations and the volunteers' reports germane to human factors issues are presented here by topic area.

Extremity Armor Donning and Doffing

Upon first being exposed to each type of extremity armor at the beginning of the study, the volunteers required a demonstration of the manner in which the components of each configuration were to be put on and adjusted for a proper fit. After practice, volunteers could don and doff each type of body armor properly and without assistance. Difficulties were encountered securing the deltoid protectors on the DP/LEBA around the upper arm, a task that had to be done with one hand. Difficulties were also encountered with mating the zipper that ran vertically on the lower leg of the QuadGuard once the trousers had been donned. With experience, the volunteers checked to see that the zipper was mated before they put on the trousers.

Interference of Extremity Armor With Movement

During the human factors portion of the study and throughout the rest of testing, volunteers were queried frequently by the investigators regarding any specific restriction or interference with movements that they attributed to the extremity armor. The majority of volunteers reported that the QuadGuard was restricting in the hip area and at the front of the knees. The restrictions were experienced while climbing stairs or squatting down. The majority of volunteers found the IDAS to restrict movement of the upper arm and shoulder when throwing grenades. The majority of volunteers reported that tightening of the knee pads of the LEBA to keep them in place resulted in restriction at the back of the knee when the knee was flexed.

Compatibility of Extremity Armor With Military Equipment and Activities

Study activities involved use of individual equipment, in addition to the IBA and the extremity armor systems, and investigators noted any compatibility issues. Also, during the human factors portion of the testing, the volunteers, wearing the various types of armor, assumed prone and kneeling firing positions and sighted using a mock M-4 carbine. In addition, the volunteers put on the MOLLE large rucksack in conjunction with wear of the armor. The investigators made observations of compatibility and elicited verbal feedback from the volunteers.

The volunteers used the Advanced Combat Helmet on a number of occasions during testing. None of the different types of armor interfered with wear of the helmet. The three extremity armor systems were also compatible with wear of the IBA. There were compatibility issues observed when the armor was worn with the MOLLE large rucksack. With all three types of extremity armor, the waist belt of the rucksack had to be secured over the trousers of the extremity armor, and the waist belt could not be tightened securely enough to distribute the rucksack load to the wearer’s hips. Further, when the QuadGuard jacket or the deltoid protectors of the DP/LEBA were worn, the shoulder straps of the MOLLE lay over the edges of the shoulders, extending on to the upper arms, rather than lying over the top of the shoulders.

The volunteers successfully assumed a kneeling firing position and aimed their weapons, regardless of the armor worn. However, when in a prone firing position, some volunteers could not “pocket” the weapon against the shoulder properly while wearing the QuadGuard jacket or the deltoid protectors of the DP/LEBA.

During vigorous activity, such as running and jumping, it was observed that the lower leg portion of the LEBA sometimes slid down the leg and over the top of the boot to rest on the foot portion of the boot. The knee pads of the LEBA also slid down to the ankles on occasion during vigorous activities. The volunteers tried to prevent this by tightening the retaining strap of the knee pads. However, the volunteers reported that tightening of the knee pads of the LEBA to keep them in place resulted in restriction at the back of the knee when the knee was flexed.

Subjective Measures

In addition to eliciting verbal feedback from the volunteers, the investigators administered questionnaires to the volunteers at preestablished points during testing. The 15-category Borg (1970) RPE rating scale (Appendix A) was administered throughout the study to assess the perceived exertion associated with wearing a particular armor system while performing a particular activity. The RPSD questionnaire (Appendix B; Corlett & Bishop, 1976) was also administered on numerous occasions to obtain ratings of pain, soreness, discomfort, or restriction experienced by the volunteers as they executed testing activities in a given armor system. In addition, the investigators devised study-specific questionnaires to query the volunteers about particular aspects of the armor systems. These questionnaires were administered toward the end of testing, after the volunteers had extensive experience wearing all the armor systems. The findings on the subjective measures used in this study are reported here.

Borg Scale RPEs

The mean RPE ratings given at the conclusion of the 10-min treadmill walks at 1.34 $m \cdot s^{-1}$, the 10-min treadmill runs at 2.24 $m \cdot s^{-1}$, the obstacle course runs, and the 30-m rushes are presented in Figure 21, along with the results of the statistical analyses performed on the data. Regardless of armor condition, the volunteers gave the highest exertion ratings at the end of the obstacle course runs and the lowest at the end of the 10-min treadmill walks. Significant differences were found among the armor conditions in the ratings given for the 10-min treadmill runs and the obstacle course runs. On the treadmill runs, the DP/LEBA and the QuadGuard were given significantly higher exertion ratings than the IBA. The ratings given the IDAS did not differ from those given to the IBA or to the other extremity armor configurations (Figure 21). For the obstacle course runs, the three types of extremity armor had ratings that were significantly higher than those given for the IBA. There were no significant differences among the extremity armor conditions.

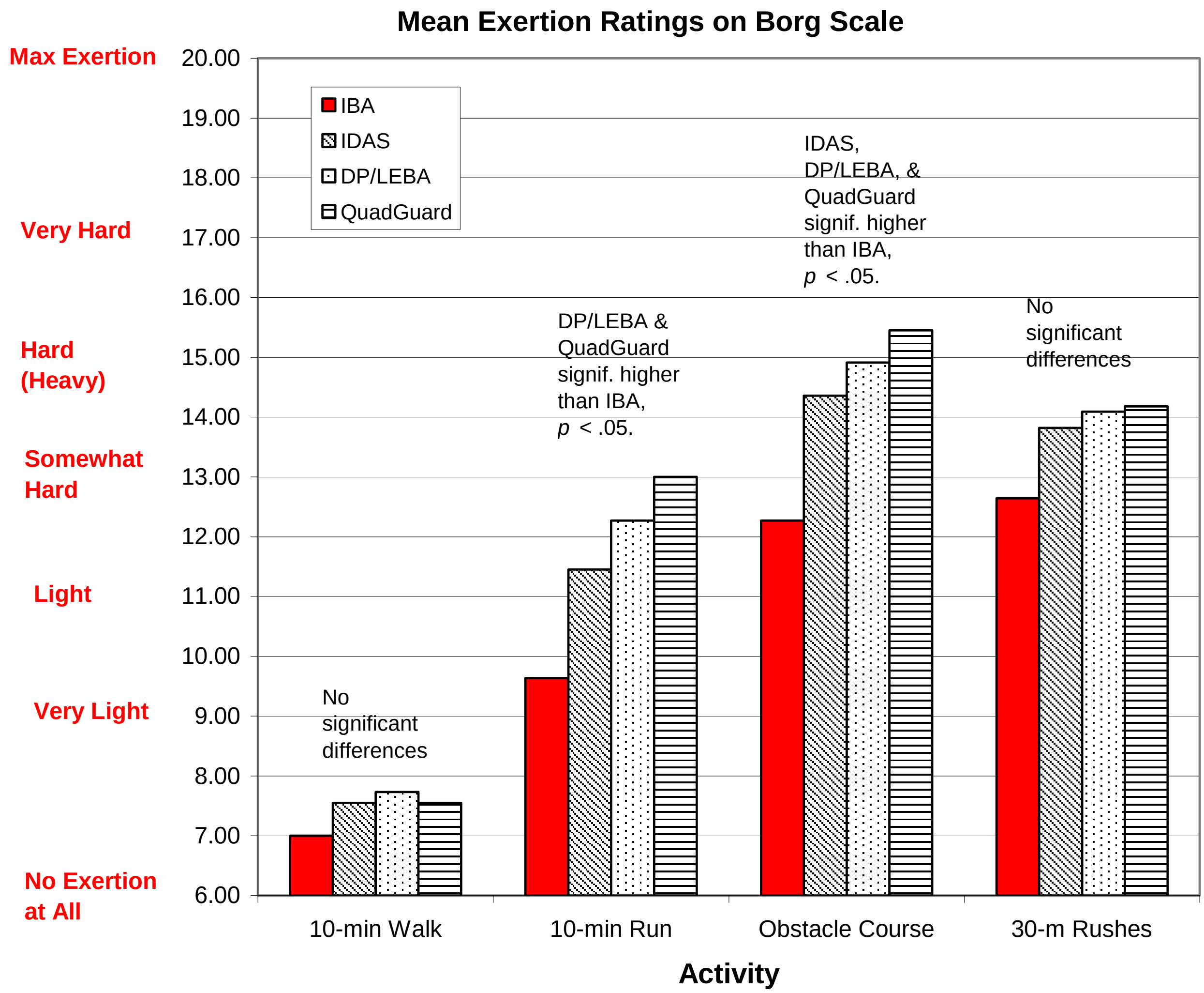


Figure 21. Means on the Borg RPE scale for each armor condition and results of post-hoc tests (N = 11).

Ratings of Pain, Soreness, Discomfort, and Restriction and Responses on Study-Specific Questionnaires

On the RPSD, the volunteers were to use a 5-point scale, which ranged from *none* to *extreme*, to rate the pain, soreness, discomfort, or restriction that they experienced on specific parts of their bodies. The vast majority of ratings given were *none* or *slight*. The 10-min treadmill runs at 2.24 $m \cdot s^{-1}$, the grenade throws, and the repetitive box lift and carry elicited ratings of at least *slight* discomfort or restriction from a higher proportion of volunteers than the other study activities did. In Figure 22, the percentages of volunteers who gave a rating of at least *slight* discomfort on each of these three tests are presented for each armor condition. A lower proportion of volunteers reported at least *slight* discomfort with the IBA than with the extremity armor. Of the three types of extremity armor, the QuadGuard tended to receive the highest proportion of ratings of at least *slight* discomfort.

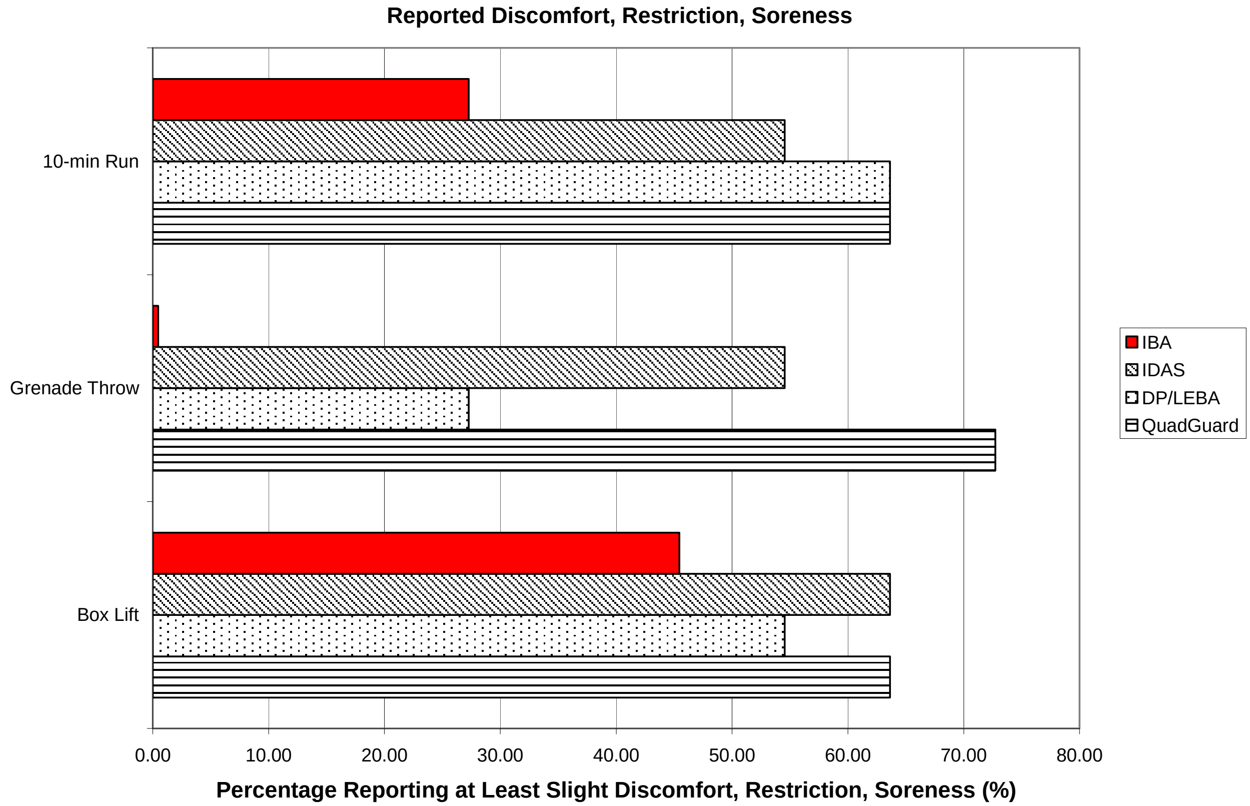


Figure 22. Percentages of volunteers giving ratings of at least *slight* discomfort, restriction, or soreness for each armor condition and three activities (N = 11).

On one of the questions, the volunteers rated, on a 5-point scale (from *very difficult* to *very easy*), the ease or difficulty of performing a number of simple movements. The average rating for each of these movements is presented in Figure 23 for each armor condition. As can be seen in the figure, the ratings were generally neutral or on the positive (*easy*) side of the scale. Further, the IBA received more positive average ratings than the extremity armor did. Among the three types of extremity armor, the QuadGuard received the lowest average ratings for ease of performing the simple movements.

On another question, the volunteers considered, based upon their military field experience, whether or not the IBA and the various types of extremity armor would be compatible for use in various military environments. The percentages of volunteers reporting positively with regard to compatibility of the armor in the different environments are presented in Figure 24 for each armor condition. All the volunteers judged that the IBA would be compatible for use in the environments listed, and a high percentage of them judged that the IDAS would be compatible. The QuadGuard received the lowest percentage of affirmative responses.

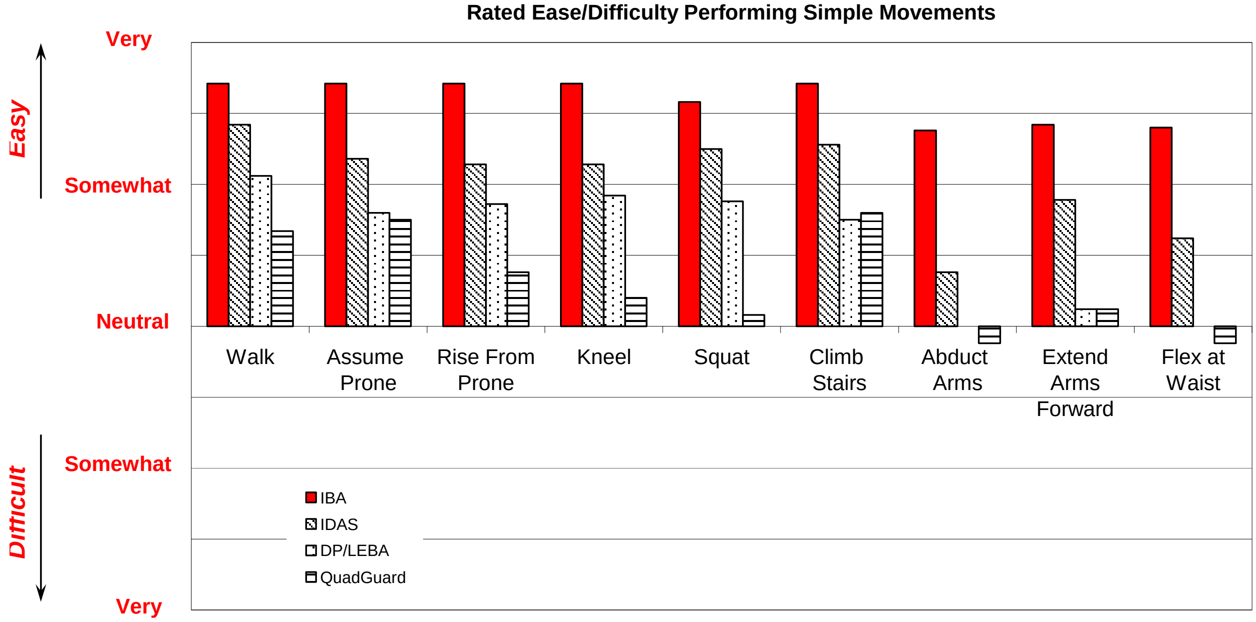


Figure 23. Average ratings of ease/difficulty of performing simple movements for each armor condition (N = 11).

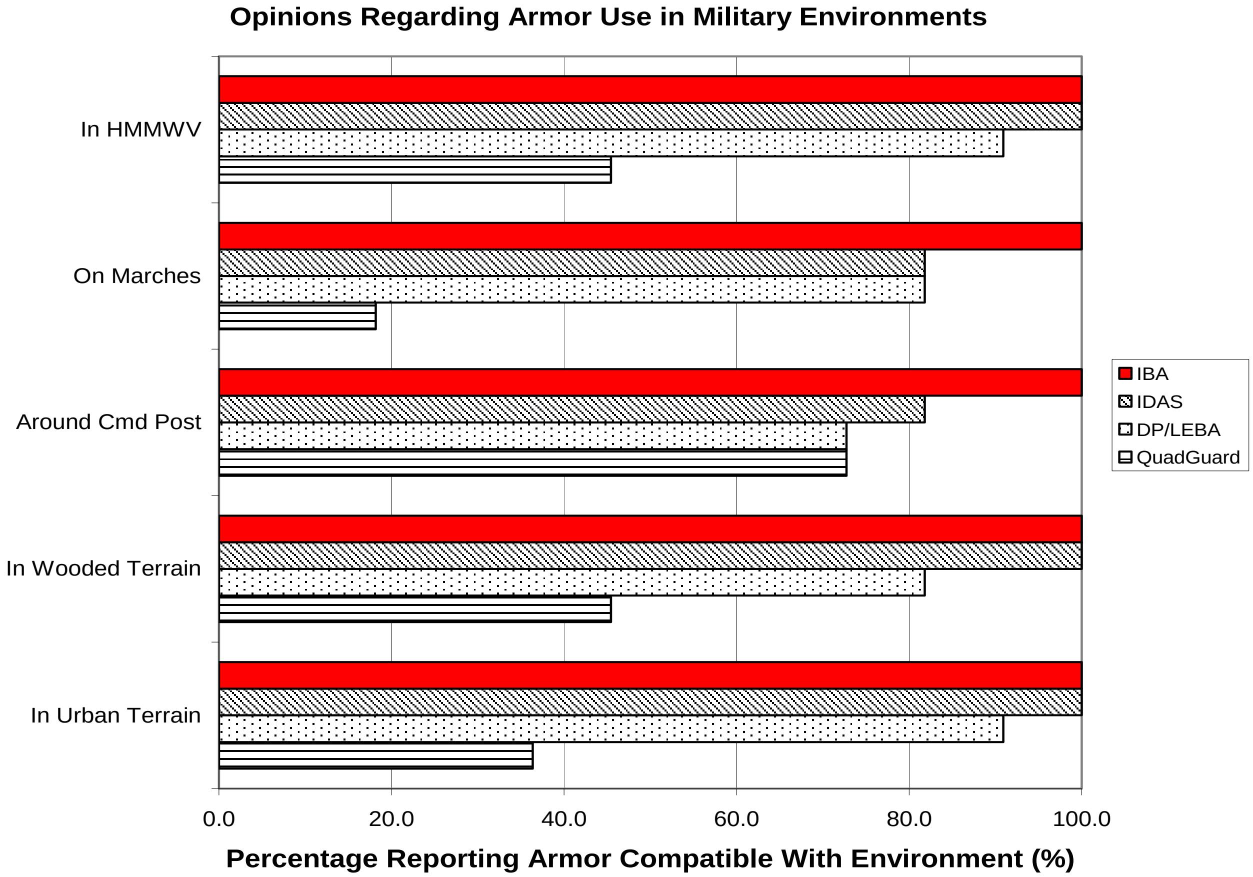


Figure 24. Percentages of volunteers reporting armor as compatible with use in specified military environment (N = 11).

To assess their opinions of the characteristics of the four types of armor, the volunteers were given a list of pairs of bipolar adjectives related to armor characteristics (e.g., heavy-light, hot-cool), and were asked to rate each adjective pair using a 7-point scale (from *extremely heavy* to *extremely light*, *extremely hot* to *extremely cool*, etc.). The average ratings given for each pair for each type of armor are presented in Figure 25. The volunteers generally gave more positive/ fewer negative ratings to the IBA and the IDAS than to the DP/LBA and the QuadGuard.

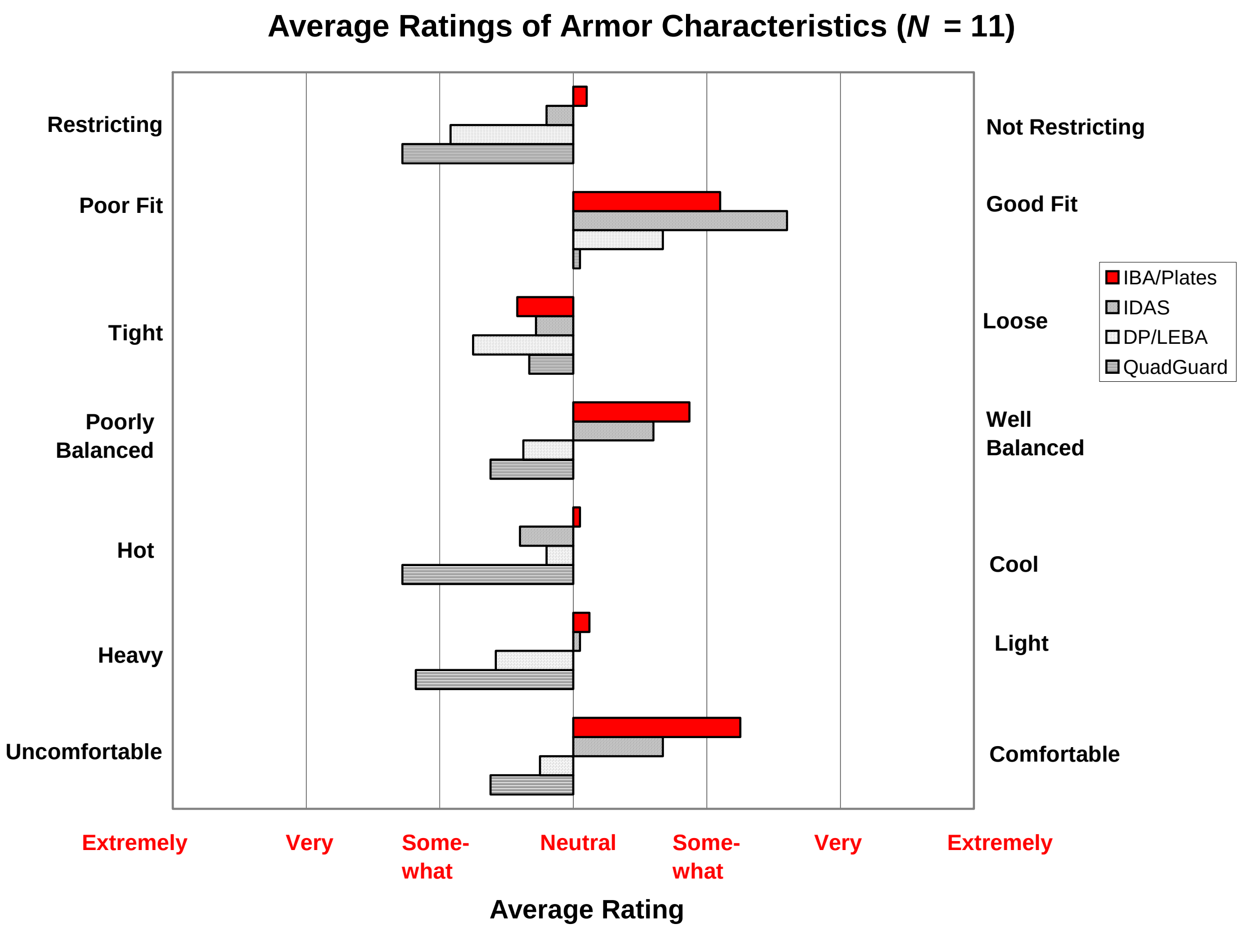


Figure 25. Average ratings for bipolar adjectives for each armor condition (*N* = 11).

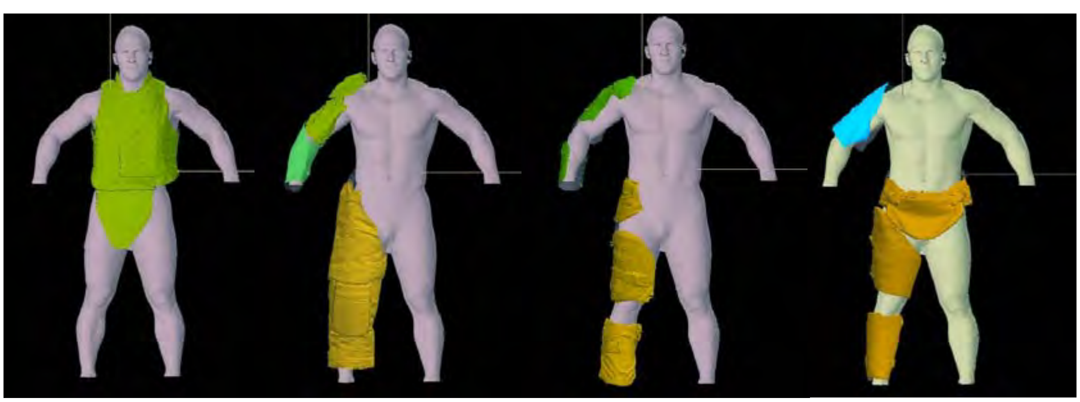
On two questions posed at the completion of testing, the volunteers were to select the one type of extremity armor that they most preferred and the one type that they least preferred. They were also asked to give reasons for their selections. The IDAS was selected as most preferred by 10 of the 11 volunteers; the remaining man selected the DP/LEBA as his most preferred system. With regard to the least preferred system, 10 of the 11 men selected the QuadGuard, and one man selected the DP/LEBA. The reasons given by the volunteers who favored the IDAS and those who least preferred the QuadGuard are presented in Table 9.

Table 9. *Reasons Given by the Volunteers for Their Selections of Most and Least Preferred Extremity Armor Systems (N = 11)*

Most Preferred Extremity Armor: IDAS (Selected by 10 of 11 Volunteers)
— Good coverage of the body without bulk
— Flexible, good mobility, not restricting
— Light weight
— Cool
— Good fit
Least Preferred Extremity Armor: QuadGuard (Selected by 10 of 11 Volunteers)
— Bulky
— Inflexible, poor mobility, restricts and slows movement
— Heavy
— Hot, does not breath
— Poor fit (trousers baggy, arms too long), too much material
— Noisy to move in

Armor Area of Coverage

The ballistic-protective coverage provided to the extremities by the three types of extremity armor was obtained from 3D scans of volunteers in a baseline IBA-armor condition and in each of the extremity armor conditions. The body surface area covered by ballistic-protective material was calculated for the individual. An example of the 3D scanned image of a representative volunteer used for the calculation of armor coverage is shown in Figure 26; only the right side of the body coverage is shown.



IBA QuadGuard IDAS DP/LEBA

Figure 26. Example of 3D scans for ballistic coverage calculations.

The mean body surface area covered by ballistic-protective material for each type of armor is presented in Table 10. The mean ballistic coverage area for each extremity armor condition does not include the area covered by the IBA and the groin protector attached to it. The QuadGuard was found to have a significantly greater ballistic area of coverage than the other extremity armors tested, and the IDAS was found to have the least area of coverage.

Table 10. *Means and SD for Body Surface Area Covered by Ballistic-Protective Material for Each Armor Type (N = 11)*

	Armor Coverage (in.^{2})			
Statistic	IBA	IDAS	DP/LEBA	QuadGuard
Mean	$4104.77_{\mathbf{C}}$	$3060.84_{\mathbf{A}}$	$3639.18_{\mathbf{B}}$	$5145.70_{\mathbf{D}}$
SD	325.82	512.88	394.24	333.37

Note. The coverage value for the IBA includes the groin protector. The IBA coverage is not included in calculations of body surface area coverage for the extremity armor. Means that do not share the same subscript differed significantly in the post-hoc tests ($p < .05$).

DISCUSSION

Statistical analyses of a number of the objective measures that were taken on the armor conditions tested in this study revealed significantly better outcomes with the configuration that included only the IBA than with any of the configurations that also included extremity armor. However, there were some measures on which at least one of the three types of extremity armor studied did not differ significantly from the IBA. Results of the physical performance tests are illustrative of this aspect of the study findings.

One of the performance tests, the grenade throw, required a very light level of physical activity. Here, the armor worn did not affect the outcome measures, which were grenade throw distance and accuracy. The box lift and carry performance test was more physically demanding than the grenade throw: Volunteers were encouraged to move as rapidly as possible when lifting and carrying the 20.5-kg box. However, the volunteers had to walk only a short distance during each cycle, and the volunteers paced their work so as to complete the entire 5 min of the task without becoming overly fatigued. On this test, the number of cycles of lifting and carrying completed with the IBA was significantly superior to the number completed with two of the three types of extremity armor. On the obstacle course run, a third physical performance test, upper body strength and maneuverability were elements of the activity, but maximal speed of movement was heavily involved in executing the test. Maximal speed was also the main element of the 30-m rushes. For both of these tests, completion times were significantly shorter with the IBA than with any of the three types of extremity armor. Times were 13 to 18% faster on the obstacle course and 6 to 10% faster on the rushes with the IBA only than with the addition of the extremity armor. Thus, it would appear that performance impairments associated with use of extremity armor, when compared to use of torso armor alone, are more likely to occur on physically demanding activities requiring speed of movement, a finding probably attributable to the weight of the extremity armor.

Consequences of the Weight of the Extremity Armor

The extremity armor used in this study added considerably to the load that the volunteers were bearing on their bodies. The mass of the clothing plus the mass of the IBA, including SAPI plates, totaled 19% of the volunteers' average body mass. The three types of extremity armor were highly similar in weight, differing by less than 1 kg. When this armor was used, the mass of all the items worn or carried by the volunteers was increased to about 26% of average body mass. Findings from past research on armor vest use and on load carrying support the postulation that extremity armor weight had a negative influence on execution of the more physically demanding performance tests used in this study (Ricciardi et al., 2008; Treloar & Billing, 2011). Investigations comparing completion times of obstacle course runs and other maximal performance tests with and without backpack loads found that times increased substantially when a load was carried (Frykman et al., 2001; Harman et al., 1999a, 1999b). Also, in reporting on effects of increasingly heavy loads, Polcyn et al. (2002) provided data indicating that completion times on maximal performance tests increase in a linear fashion with load mass increases.

The energy consumption data from the 10-min periods of walking at 1.34 $m \cdot s^{-1}$ and running at 2.24 $m \cdot s^{-1}$ on a level treadmill provide some insight into the manner in which armor

weight influenced the volunteers' basic physiological processes. The measure of energy consumption used in this study was $\dot{V}O_2$. After $\dot{V}O_2$ was adjusted for the volunteers' body masses, the energy used during walking and running was found to be significantly lower with the IBA alone than with the addition of any of the three types of extremity armor. Compared with the IBA, oxygen consumed per unit body mass when wearing the extremity armor was 22 to 26% higher during walking and 7% higher during running. The higher ratings on the Borg scale given to the extremity armor conditions indicated that the volunteers themselves perceived that the walking and the running exercises were more strenuous with the extremity armor than with the IBA alone. Investigators have reported that walking in an armor vest increases physiological strain compared with no armor worn (Cheuvront et al., 2008; Martin & Nelson, 1982, 1986; Ricciardi et al., 2008). The results of this study indicate that the additional load on the body imposed by use of extremity armor, as well, will contribute further to the physiological burden.

Energy usage is a critical consideration in assessing differences among the armor configurations tested here because higher energy consumption when executing physical activities has negative implications for military operations. During prolonged bouts of walking and running under field conditions, for example, with higher energy consumption, there is an increased probability that personnel will slow their pace or take more frequent rests. Efficiency in executing physically demanding tactics may also decrease because of the greater exertion required. Although they walked and ran for only 10 min at a time, the volunteers in this study reported that these walking and running exercises were more strenuous with the extremity armor than with the IBA alone. In the study, the speed and duration of the bouts of walking and running were imposed by the investigators, and thus the volunteers could not lower their activity levels to lower their exertion. In a military field situation, however, personnel might well lower their activity levels, if circumstances permit, in order to sustain prolonged exercise and minimize fatigue.

Like the analysis of energy consumption, the analyses of the biomechanical data provide information regarding the influence of armor weight during walking and running. The measures of GRF were normalized to the volunteers' body masses and then analyzed. From analyses of the vertical component of GRF during walking, it was found that the forces at heel-strike and at toe-off were significantly lower in magnitude with the IBA than with any of the types of extremity armor. The addition of the extremity armor increased the forces by about 6% relative to the forces with the IBA alone. The running data were analyzed for vertical force at heel-strike, and values for the IBA were found to be significantly lower than those for two of the three extremity armor conditions. The forces for these two conditions were 6% greater than the magnitude of the force for the IBA alone.

Even when only minimal clothing is worn, vertical GRFs associated with locomotion can be very high. In this study, the vertical GRFs during walking in the IBA alone were 30% greater than the volunteers' mean body weight, and during running in the IBA, they were about 2.3 times mean body weight. These findings are in consonance with reports from investigations in which gait kinetics were examined for effects of varying the masses of load-bearing equipment (Harman et al., 1999a, 1999b; Polcyn et al., 2002). Repeated exposures of the body to the high vertical forces that occur every time the foot contacts and subsequently pushes off from the ground during walking and running have been postulated to contribute to the onset of acute and

chronic injuries, particularly overuse injuries of the lower extremities (Knapik et al., 1996). A possible consequence of increasing already high vertical GRFs by adding extremity armor or other items that further increase the external load on the body is to increase the probability of incurring such injuries.

The results for the $\dot{V}O_2$ and the GRF variables recorded during walking and running that have been considered up to this point in the discussion were obtained from analyses of the raw data adjusted to account for the volunteers' body masses. Additional analyses were carried out on the $\dot{V}O_2$ and the GRF variables using data adjusted to total mass, including body mass and the mass of the extremity armor, the IBA, and of all other items being worn. Analyses of these data did not yield significantly higher energy consumption or higher magnitude vertical GRFs with the extremity armor than with the IBA.

Effects of Design Characteristics of the Extremity Armor

Taken together with the data adjusted for the volunteers' body masses, the findings from the analyses of data adjusted for total mass confirm that there was a weight penalty associated with wear of the extremity armor. In addition, they indicate that other aspects of the extremity armor, such as design characteristics, did not contribute to the increased energy cost and forces on the body during walking and running. However, there were measures taken in the study that did appear to be affected by differences in design among the three types of extremity armor. An example is the time to complete the 30-m rush maximal performance test. Wear of the QuadGuard resulted in the slowest completion times. Times with the IDAS and the DP/LEBA were significantly faster and did not differ significantly from each other. With the QuadGuard, ballistic material covered a substantially greater portion of the surface area of the body than it did with the IDAS and the DP/LEBA. It is possible that movements of the lower extremities were encumbered with the QuadGuard to the extent that running during the 30-m rushes was slowed.

The analyses of the ranges of movement of the hip and the leg in flexion provide some support for positing that the QuadGuard encumbered locomotor movements to a greater extent than the IDAS and the DP/LEBA: In both of these tests, the extent of movement was significantly lower with the QuadGuard than with the other two types of extremity armor. Analyses of gait kinematics for treadmill walking also suggest an encumbrance of lower extremity movements with the QuadGuard. Stride length was shorter and stride cycle time was faster with the QuadGuard than with the other two types of extremity armor, but the differences among the extremity armor conditions were not statistically significant.

Another of the gait variables, stride width, would be expected to be affected by thickness of material in the crotch or the thigh areas. In analysis of the treadmill walking data, both the QuadGuard and the DP/LEBA were associated with greater stride widths than the IDAS, but the differences among the types of extremity armor were not statistically significant. The treadmill running data yielded somewhat similar findings. Here, stride widths with the QuadGuard and the IDAS were greater than that with the DP/LEBA, but not significantly so.

It is of note that the analyses of the stride length and the cycle time data for running did not yield any significant differences among the extremity armor conditions. Indeed, the values

for the extremity armor did not differ from the value for the IBA alone on these two variables. The aspects of running gait that resulted in it being less sensitive to armor manipulations in this study than walking gait are not known.

Several of the activities performed in this study required movement of the upper extremities. Two of these, arm abduction and shoulder flexion, involved movement of the arm at the shoulder to the maximum extent possible. In both tests, range of motion was significantly less with the DP/LEBA than with the IDAS and the QuadGuard. Another test involving arm-shoulder movements was the grenade throw. Compared with the distance and the accuracy achieved with the IDAS and the QuadGuard, there was no indication that wearing of the DP/LEBA interfered with the throwing movements. Furthermore, in feedback regarding the test, volunteers reported that they experienced greater restriction with the IDAS and the QuadGuard than with the DP/LEBA. However, the restrictions reported in the case of the QuadGuard were not associated with the throwing movement itself, but with the squatting posture that the volunteers were required to maintain before they stood to throw the grenades.

Flexing of the upper torso at the waist was another movement that the volunteers were required to perform in the course of testing, specifically on the standing trunk flexion task. It was found that the extent of movement was somewhat less with the IDAS than with the DP/LEBA and significantly less with the IDAS than with the QuadGuard. The IDAS was designed with a belt and ballistic-protective material that covered portions of the waist and hip areas. It is possible that the bulk around the waist and hips limited flexion at the waist when the IDAS was worn.

In addition to design differences among the three types of extremity armor reflected in the objective measures, the volunteers, in their feedback during testing and in their responses on study questionnaires, reported design differences that they perceived as affecting the functionality and the comfort of the extremity armor. Among them were difficulties pocketing the rifle butt against the shoulder when the QuadGuard or the DP/LEBA was worn because of the designs of the shoulders of these systems. Further, none of the extremity armor systems was compatible with use of the waist belt of the MOLLE large rucksack because the waist belt of the rucksack could not be adjusted properly over the trouser portions of the extremity armor. Also, the lower leg portions and the knee pads of the LEBA slid down the leg during vigorous exercise. The lower leg portions were individual pieces with buckles and straps to secure each piece to itself, but there was no way to attach the pieces to the upper leg pieces or to any other part of the system. Therefore, the lower leg pieces were not prevented from working their way down the legs. The situation with the knee pads was similar; a buckle and strap were the only means to keep a knee pad in place. In addition, comments regarding the QuadGuard indicated that the trousers restricted movement in the hip area and at the front of the knees, and the IDAS was reported to restrict arm-shoulder movement during grenade throws.

Consideration of Extremity Armor Area Coverage

The ideal extremity armor is, undoubtedly, a system that provides complete ballistic protection of the upper and lower extremities, weighs no more than a combat uniform, and does not impair performance of combat tasks to a greater extent than the combat uniform. Until the

ideal is realized, use of extremity armor to gain ballistic protection will entail the addition of weight to the body and degradation in some aspects of performance. The increased energy consumed when walking and running and the higher vertical GRFs at heel-strike and toe-off during locomotion with the extremity armor tested here compared with the IBA alone are illustrative of the weight-related penalty incurred.

The three types of extremity armor evaluated were approximately equal in weight. They did, however, differ substantially in the total surface area of the body covered by ballistic-protective materials. The QuadGuard was highest by far in area coverage. This more extensive coverage of the body did not prevent users of the QuadGuard from carrying out any of the study-related physical activities. However, considering the overall results from this study, performance with the QuadGuard differed from that with the IBA alone to a somewhat greater extent than performance with the other two extremity armor systems did. The QuadGuard was also the extremity armor system least preferred by the volunteers. The volunteers rated the QuadGuard as being heavy relative to the other two systems, although, in fact, all three systems were similar in weight. The volunteers also reported that the QuadGuard was hot, bulky, and restricted movements.

The extremity armor system with the least coverage of body surface area provided by ballistic-protective material was the IDAS, and it was also the system most preferred by the volunteers. The volunteers gave the IDAS positive ratings for ease of performing basic body movements and judged it to be high in compatibility for use in military environments. In addition, the volunteers rated the IDAS positively for comfort and fit and reported that it was flexible and lightweight. In terms of overall performance on the tests included in the study, results with the IDAS were somewhat better than those with the QuadGuard and similar to those with the DP/LEBA.

CONCLUSIONS AND RECOMMENDATIONS

The findings from this study indicate that, compared with wearing only the IBA, use of extremity armor increases the energy consumed during walking and running, changes the biomechanics of gait, increases the GRFs associated with locomotion, and negatively affects performance of some militarily relevant physical tasks. Differences obtained between the IBA alone and the IBA plus extremity armor on a number of objective measures taken in this study were attributable to the weight of the extremity armor. The impact of extremity armor weight was evidenced in longer times to complete physically demanding activities requiring speed of movement. The weight also resulted in increased energy usage and higher magnitude GRFs during walking and running.

Weight was a predominant factor in distinguishing performance with the IBA alone from performance with the IBA plus extremity armor. The three types of extremity armor tested were highly similar to each other in weight, but there were design variations that yielded differences among the three systems on some of the performance measures. One aspect of design on which the systems differed was body surface area covered by ballistic-protective material. The QuadGuard, which had the greatest area coverage, encumbered movement of the lower extremities and was selected by volunteers as the extremity armor they least preferred. Based on overall results of testing, performance with the QuadGuard differed from that with the IBA alone to a somewhat greater extent than performance with the other two extremity armor systems did. The IDAS had the least body area coverage, and it was selected by study volunteers as their most preferred extremity armor system. Overall results with the IDAS were somewhat better than those with the QuadGuard and similar to those with the DP/LEBA.

Although differences among the extremity armor systems in body surface area covered by ballistic-protective material appeared to affect performance and user opinion, conclusions cannot be made from the results of this study about the influence of area coverage on the performance measures employed here. The three types of extremity armor differed in design characteristics other than area coverage, and the effects of these characteristics cannot be isolated from effects of area coverage in the data acquired in this study.

The study volunteers definitely viewed the QuadGuard least favorably and the IDAS most favorably of the three extremity armor systems. The objective measures taken in this testing, however, did not reveal extensive differences among the systems. From the results on the objective measures, there is no basis to recommend that any of the three systems not be considered further for military use. The systems were not, however, tested for the thermal burden they impose on the user. The systems may well differ in this regard due to their different area coverage.

In testing each of the extremity armor systems, observations were made by the investigators and feedback was given by the study volunteers for the purpose of identifying aspects of the design that were particularly problematic and that could be improved. Reductions in the weights of all the systems would benefit users. Other suggested modifications are:

- IDAS: Reduce the bulk in the waist and hip areas.
- DP/LEBA: Secure the lower leg pieces and the knee pads to prevent them riding down the legs. This might be accomplished by securing the lower leg pieces and the knee pads to the upper leg pieces.
- QuadGuard: Add ease to the knee areas to permit greater knee flexion. Check the sizing system with particular attention to appropriateness of hip and waist circumference dimensions, arm length, and trouser length.

This document reports research undertaken at the U.S. Army Natick Soldier Research, Development and Engineering Center, Natick, MA, and has been assigned No. NATICK/TR- 12/014 in a series of reports approved for publication.

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APPENDIX A

Sample of the Borg Rating of Perceived Exertion Scale
(Reprint of original)

Volunteer Number:______ Date:________ Test Condition:___________

Borg Scale

RPE	Exertion
6	No exertion at all
7	Extremely light
8	
9	Very light
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard (heavy)
16	
17	Very hard
18	
19	Extremely hard
20	Maximal exertion

Instructions for Borg Rating of Perceived Exertion (RPE) Scale

While doing physical activity, we want you to rate your perception of exertion. This feeling should reflect how heavy and strenuous the exercise feels to you, combining all sensations and feelings of physical stress, effort, and fatigue. Do not concern yourself with any one factor such as leg pain or shortness of breath, but try to focus on your total feeling of exertion.

Look at the rating scale below while you are engaging in an activity; it ranges from 6 to 20, where 6 means "no exertion at all" and 20 means "maximal exertion." Choose the number from below that best describes your level of exertion. This will give you a good idea of the intensity level of your activity, and you can use this information to speed up or slow down your movements to reach your desired range.

Try to appraise your feeling of exertion as honestly as possible, without thinking about what the actual physical load is. Your own feeling of effort and exertion is important, not how it compares to other people's. Look at the scales and the expressions and then give a number.

9 corresponds to "very light" exercise. For a healthy person, it is like walking slowly at his or her own pace for some minutes

13 on the scale is "somewhat hard" exercise, but it still feels OK to continue.

17 "very hard" is very strenuous. A healthy person can still go on, but he or she really has to push him- or herself. It feels very heavy, and the person is very tired.

19 on the scale is an extremely strenuous exercise level. For most people this is the most strenuous exercise they have ever experienced.

Borg RPE scale

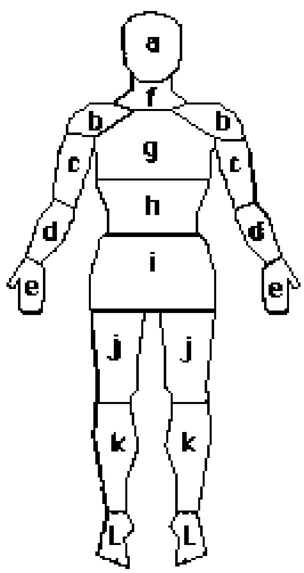
APPENDIX B

Sample of the Rating of Pain, Soreness, and Discomfort Questionnaire
(Reprint of original)

Discomfort Questionnaire:

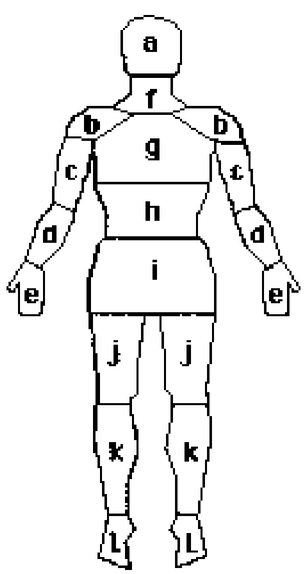
Volunteer Number:______ Date:________ Test Condition:___________

1. Rate the degree of PAIN, SORENESS, or DISCOMFORT that you are currently feeling for Body Parts A through L. Do so for the FRONT and the BACK of the body.



FRONT of Body

	a	b	c	d	e	f	g	h	i	j	k	L
NONE	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
SLIGHT	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
MODERATE	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
SEVERE	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
EXTREME	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐



BACK of Body

	a	b	c	d	e	f	g	h	i	j	k	L
NONE	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
SLIGHT	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
MODERATE	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
SEVERE	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
EXTREME	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐